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# The Joy of Science

## Course Guidebook


Professor Robert M. Hazen
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Professor Hazen is active in presenting science to a general audience. His articles on science for a general readership have appeared in *Newsweek*, *The New York Times Magazine*, *Smithsonian Magazine*, *Technology Review*, and *Scientific American*. At George Mason University he has developed courses and companion texts on scientific literacy. His books include the best selling *Science Matters: Achieving Scientific Literacy* and *The Sciences: An Integrated Approach*. Hazen serves on advisory boards of the National Committee for Science Education, NOVA (WGBH TV Boston), *Encyclopedia Americana*, and the Carnegie Council. He appears frequently on radio and television programs on science.

Robert Hazen is also a professional trumpeter. He has performed with numerous ensembles, including the National Symphony Orchestra, the

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# The Joy of Science (Lectures 1–12)

**Scope:**

Part I of our exploration of the central concepts of science begins with an examination of science as a way of knowing (Lectures 1 and 2), and then considers the overarching phenomena of forces and motions (Lectures 3–6), energy (Lectures 7–10), and magnetism and electricity (Lectures 11 and 12). Of the many ways devised to understand our place in the cosmos, science holds a special place as a method designed to ask and answer questions about tangible aspects of the physical world. Scientific knowledge depends on independently verifiable data obtained from observations, experiments, and theoretical reasoning.

The scientific method, in its idealized form, is a cycle of observation, synthesis, hypothesis, and prediction that leads to more observations. This process developed gradually, coming to full flower in the 16th century with the work of Nicolas Copernicus and subsequent astronomers on the nature of celestial motions, as well as Galileo Galilei and his contemporaries on the laws of terrestrial motion. Isaac Newton synthesized these seemingly separate areas of research in his universal laws of motion and gravitation.

Energy, the ability to do work, is essential in every endeavor, yet its scientific description is difficult and abstract. Two laws of thermodynamics systematize the behavior of energy. The first law states that while energy occurs in many interchangeable forms, the total amount of energy is constant. The second law of thermodynamics states that energy tends to spread out, shifting from more useful to less useful forms.

Newton's laws established a systematic approach to the study of forces, such as magnetism and electricity, which were long thought to be unrelated phenomena. The invention of the battery, and subsequent studies of electrical phenomena, set the stage for the synthesis of electricity and magnetism. ■

# The Nature of Science

## Lecture 1

**To begin, we need to examine what makes science special. We need to think about science as a way of knowing. So, I ask you, how do you know what you know? Humans have devised many different ways of knowing. We have religion, we have philosophy, there's the arts, there's ethics, and, of course, there's science.**

Science holds a special place as a method designed to ask and answer questions about the tangible aspects of the physical world. Science is based on reproducible observations, controlled experiments, and theoretical reasoning. Science is fundamentally different from other ways of knowing because it is based on independently verifiable facts about physical phenomena, for example:

- Science differs from religion, which depends on revealed truth.
- Science differs from the arts, which depends on each artist's unique vision.
- Science differs from political science and social science, in which the richness of the discipline results from a multiplicity of interpretations of past and future events.
- Science differs from pseudo-sciences, which are not based on reproducible and independently verifiable observations.

The process of science provides a powerful tool for observing the world, learning how it works, making predictions about future events, and discovering ways to modify our surroundings.

In the modern world, all citizens need to be scientifically literate. Scientific literacy helps consumers make informed decisions. Science content provides a basis for understanding how and why products work; the scientific process

of inquiry provides a framework for critical thinking about personal choices. Scientific literacy is advantageous for many reasons:

- Many jobs depend on science, as well as on the technologies that are developed from scientific discoveries. Modern medicine, law, and business all depend on science.

- Scientific literacy is the very foundation for teaching children about their world. Parents and teachers who are scientifically literate can reinforce a child's natural curiosity by exploring the natural world together.

- Scientific literacy also allows a person to share the richness of humanity's great ongoing adventure of discovery and exploration. Every day, scientists are discovering and sharing new things that no human ever knew before.

Everyone can achieve scientific literacy. The great principles of science can be presented without relying on complex vocabulary or mathematical abstraction. Several contrasting definitions of scientific literacy have confused the issue and hindered science education reform. Scientific literacy is not technological literacy, nor is it the stepping stone exclusively for future scientists. You do not have to be a scientist to appreciate the great discoveries of science.

**Science is a way of knowing about the natural world, based on reproducible observations and experiments.**

The National Science Education Standards represent a consensus of thousands of scientists and educators regarding the content and presentation necessary for all citizens to achieve scientific literacy. This document provides a sound building code for science curricula:

- Scientific literacy is based on understanding a few overarching principles, rather than extensive vocabulary and factual information.

- Scientific literacy is also based on understanding the scientific method—the process of inquiry by which questions about the natural world are asked and answered.

The objectives of this lecture series are to introduce the great principles of science—to explore how scientists discovered these sweeping ideas, and to show how the great principles come into play in our lives, in often surprising and wonderful ways.

Science is a human endeavor, with its own distinctive organizational structures. The rigid division of science into separate departments may have hindered scientific literacy of nonscientists, but there is a rationale to this structure. In fact, there is a clear hierarchy of scientific disciplines.

Physics, the study of matter in motion, is first in this hierarchy, because the laws of physics must apply to every natural system—large or small, living or inanimate. Classical physics deals with the everyday phenomena of matter, energy, forces, and motion. Modern physics deals with realms beyond our daily experience: very small, very massive, and very fast objects require new physical laws, as codified in the fields of quantum mechanics, nuclear physics, particle physics, and relativity.

Chemistry is the study of atomic interactions, especially the study of chemical reactions and the formation of new materials. Modern chemistry is rooted in alchemical studies of the Middle Ages; it is an empirical science in which inspired guesswork often leads to major advances. Chemical research and chemical engineering are closely linked. It is often possible to scale up an experimental discovery made in a test tube to a full-scale manufacturing operation.

Earth science is the study of the origin, present state, and dynamic processes of the Earth, as well as other nearby planets. Earth science is a young field that grew out of the practical experience of prospecting and mining. The two major fields of earth science include:

- Geology, the study of rocks and soils and their distribution.

- Geophysics, the study of earth's dynamic processes, such as tides, hurricanes, and earthquakes.

Biology is the study of living systems, which are by far the most complex objects we know. Because of its importance to health and medicine, biology is the largest and best funded of the sciences. Biology is an extremely diverse discipline because there are many ways to study living things. The most obvious applications of biology are in health and medicine.

In spite of the formal academic separation of science disciplines into physics, chemistry, earth science, and biology, the natural world is integrated and knows no such boundaries. ■

## Essential Reading

National Research Council, *The National Science Education Standards*.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 1.

## Supplementary Reading

Holton, *Thematic Origins of Scientific Thought*, Introduction and Chapter 1.

## Questions to Consider

**1.** In what ways has science affected your life in the past 24 hours?

**2.** If you were transported to a pre-science society, what would you miss most? In what ways might you benefit?

# The Scientific Method

## Lecture 2

**We all want to know things about the natural world and, as we saw in the last lecture, science is the best way to discover how the physical universe works. This process of discovery employs the scientific method, which may be idealized as a cyclic process of inquiry based on observations, synthesis, hypothesis, and predictions that lead to more observations.**

Scientific research is an outgrowth of human curiosity. Scientific progress depends as much on well-formulated questions, as on a catalogue of well-established answers. Many important questions are beyond the realm of science. Science addresses only those questions that can be answered by reproducible observations, controlled experiments, and theory guided by mathematical logic. Scientific questions are richly varied in scope and content. Most scientific questions fall into one of four broad categories:

- Existence questions ask what objects and phenomena occur in the natural world.

- Origin questions explore how natural objects and phenomena came to be.

- Process questions ask how nature works. These questions are often closely linked to inquiries about origins.

- Applied questions look for ways to manipulate the physical world to our advantage, whether curing disease, devising new materials, or modifying the environment.

Answers to old questions often lead to new questions. Scientific questions are also often interconnected in surprising ways. As scientists explore the most sweeping unanswered questions they often discover links between what seem at first to be unrelated topics. Plate tectonic models of the Earth's dynamic

interior bear directly on our understanding of life's origin and evolution. Studies of ancient mass extinctions provide models for understanding the importance of the global environment. Scientific questions also are often linked by their philosophical approach. Reductionism is based on the assumption that systems can be understood by examining the behavior of fundamental building blocks. At the opposite extreme, collective systems display properties completely unlike those of their smaller components. However some questions are not now scientific, but may be some day as our understanding grows (e.g., the nature of human consciousness). Several factors prevent us from obtaining complete answers to many scientific questions.

**The idealized scientific method is a cyclic process of inquiry, based on observations, synthesis, hypothesis, and predictions that lead to more observations.**

- Experimental error: All measurements, no matter how accurate, contain some error.

- The uncertainty principle: At the subatomic scale, every measurement alters the object being measured (see Lecture Nineteen for a more detailed discussion).

- Chaos: Many natural systems are chaotic, and thus are inherently unpredictable.

- The speed of light: Imitations are placed on us by space and time.

In spite of these and other inherent limitations on inquiry into the natural world, the methods of science provide the most effective and powerful tool we have to understand and modify our physical world.

The scientific method is a complex, variable, human process, which differs in detail from scientist to scientist, and from discovery to discovery. The method can be idealized as a cycle of observation, synthesis, hypothesis, and prediction. The first step in most scientific studies is the collection of data, including observations, measurements, and experiments. The second step

is the recognition of patterns—the search for symmetries. Most scientists have a deeply held belief that there are regularities and patterns in the physical universe. Sometimes this step involves recognizing similarities among seemingly different phenomena, such as different forms of electricity. Sometimes this step is a mathematical synthesis, fitting disparate data into one type of equation, such as Kepler's discovery of elliptical planetary orbits.

Once a pattern is found, the scientist will propose a possible explanation in the form of a hypothesis. A scientific hypothesis, theory, or law must lead to unambiguous and testable predictions, requiring a new round of observations. Consequently, a scientific theory can always be disproved by an unfulfilled prediction, but it can never be completely proved. At the center of this idealized cycle there is always a paradigm—a prevailing system of expectations about the natural world.

The scientific method is rarely followed as an exact cycle. Human imagination, intuition, and chance are vital elements of the process. The example of Dmitri Mendeleev and the periodic table of elements exemplifies the scientific method.

The scientific method is an elegant process for learning about the natural world, but it is neither intuitive nor obvious. Often an anomaly leads to new insights. When anomalies are found that violate well-tested theories and laws, it usually means that the old theory or law is a valid special case of a more general law. An everyday example is provided by the "hypothesis" that all objects fall under the force of gravity. The anomaly of a helium-filled balloon leads to deeper understanding. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?*, Preface and Prologue.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 1.

## Supplementary Reading

Barrow, *Impossibility*, Chapter 1.

Kuhn, *Structure of Scientific Revolutions*.

## Questions to Consider

**1.** Identify an unanswered question that is important to you. Does it qualify as a scientific question? If not, is the answer informed by science?

**2.** How might you apply the scientific method to questions that arise in your daily life, for example as a consumer?

# The Ordered Universe

## Lecture 3

**In this lecture, I want to tell you about the slow, but seemingly inexorable path towards our present view that the universe is governed by a few great overarching natural laws, but first I want to look at the scientific method in somewhat more detail.**

The idealized cycle of the scientific method—observations, synthesis, hypothesis, and predictions leading to more observations—seldom works. Science is a human endeavor characterized by luck and intuition, as well as mistakes and misperceptions. Honest errors in technique or execution are an inevitable part of the scientific process. The demand for reproducibility eventually eliminates these mistakes. By the same token, scientific fraud is rare because the scientific method ensures that such cases will eventually be discovered and corrected.

To modern scientists, each observation and measurement represents an objective, verifiable truth; each measurement thus has meaning. But the importance of observation has not always been obvious or widely accepted.

**Many aspects of the physical universe are regular and predictable.**

The Greek philosopher Aristotle (c. 384–322 B.C.), who was a student of Plato and tutor of Alexander the Great, recognized that the senses play an important role in understanding the natural world. But to him and to his followers, logic and reason, rather than our fallible senses, were the ultimate arbiters of truth. Many scholars prior to about 1650 accepted the writings of Aristotle and other ancient authorities in preference to observations. Galileo, for example, met resistance in the early 1600s when he first used a telescope to observe the heavens. After he discovered supposed “imperfections” in the heavens (features such as sunspots and craters on the Moon), some of his contemporaries refused to look through the telescope for themselves.

While many scholars have questioned the reliability of the senses, everyone relies to some extent on the predictability of the physical world. The simplest kind of verifiable observations are events that happen over and over again in our lives. Objects fall when dropped and adopt predictable curving paths when thrown. Most astronomical objects also have predictable paths.

Some ancient societies displayed their belief in the predictability of the Sun and Moon by constructing large monuments in which the positions of massive stones were aligned with key events in the calendar. One of the earliest examples of human's faith in the predictability of nature is found at Newgrange, Ireland, the site of a 5000-year-old burial tomb of an ancient Irish leader. Stonehenge, the great monument on southern England's Salisbury Plain, also served as an elaborate and sophisticated calendar.

Science depends on maintaining meticulous records of observations. Such was the lifelong task of the encyclopedist, Gaius Plinus Secundus (AD 23–79), better known as Pliny the Elder. Pliny led a rich and varied life as a cavalry officer in Germany, a naval commander at Naples, a lawyer, and an

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**Stonehenge, in Wiltshire, England, is a prehistoric celestial calendar.**

administrator in Rome's Spanish colonies. He is best remembered for his encyclopedic *Natural History*, which is divided into 37 books, each of which tabulates facts known to him directly or through reliable sources. Pliny died while observing an eruption of Mt. Vesuvius in AD 79.

To many ancient cultures, knowing the positions of the Moon and planets was of great importance both for astrological predictions and for navigation. The thousands of visible stars form a constantly rotating backdrop of constellations against which planetary motions can be plotted. The position of a planet can be measured night-by-night by its position relative to the fixed stars. Planetary motions are complex. Mars, for example, appears to move forward through the Zodiac for much of the year, only to slow and backtrack every few months. Explaining this "retrograde" motion was the major challenge in devising models of the solar system.

One of the first descriptions of the heavens that led to testable predictions of planetary positions was the extremely successful model of Ptolemy of Alexandria (c. AD 100–170). Ptolemy, an Egyptian-born Greek, collected his own observations along with those of earlier Babylonian and Greek astronomers. Ptolemy argued that the Earth must be at the stationary center of the universe. The Ptolemaic model postulated perfect circular orbits on which smaller circular paths (epicycles) were superimposed. The use of circular orbits was dictated by a belief in the perfection of the heavens. In spite of its complexity, the Ptolemaic system was reasonably successful in predicting planetary positions, and it was employed for more than 1400 years. It was not until the 1500s that new, more precise observations and application of the scientific method led to general acceptance of a competing model. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 2.

## Supplementary Reading

Cohen, *Birth of a New Physics*, Chapters 1–3.

Hawkings, *Stonehenge Decoded*.

## Questions to Consider

**1.** Imagine yourself living in a primitive society. How might you attempt to convince other people that the universe is regular and predictable? What might be their counter arguments?

**2.** Given the observations that you can make yourself without the benefit of a telescope or space travel, is it more reasonable to conclude that the Sun orbits the Earth, or vice versa?

# Celestial and Terrestrial Mechanics

## Lecture 4

**My objective in this lecture is to introduce four key individuals who transformed our understanding of the heavens.**

Science is a collective human endeavor, advanced by thousands of little-known researchers who, step-by-step, add to the store of human knowledge. Yet the history of science often must focus on the seminal contributions of a few extraordinary individuals who played pivotal roles in synthesizing previous ideas. This lecture introduces four key scientific figures of 15th- and 16th-century Europe: Nicolas Copernicus, Tycho Brahe, Johannes Kepler, and Galileo Galilei.

Polish astronomer Nicolas Copernicus (1473–1543) was trained in theology and spent nearly half a century working for the Catholic church. Yet, for reasons that remain uncertain, he devoted much of his life to constructing a mathematical model of the solar system in which the Earth and other planets orbit the Sun—a rival hypothesis to the prevailing Ptolemaic Earth-centered model. Copernicus never sought personal recognition for this theoretical scholarly effort, and the model remained unpublished until 1543, the year of his death.

In his great work, *On the Revolutions of the Celestial Spheres*, Copernicus proposed the modern model, with the Earth and other planets orbiting the Sun. He noted that for the stars to orbit the Earth, they would have to travel at enormous speeds. The model explained the retrograde motion of Mars and other planets, which was a consequence of the Earth swinging from one side of the Sun to the other during its orbit around the Sun. The model still relied on perfect circular orbits and small epicycles. The Copernican model led to greatly improved predictions of planetary positions, which led to its acceptance. The year 1543 also saw the publication of the seminal work in human anatomy, *On the Fabric of the Human Body*, by the great Flemish physician Andreas Vesalius (1514–1564), with magnificent illustrations crafted in Titian's studio.

The Copernican model of the solar system had to be tested, and that task fell principally to Danish astronomer Tycho Brahe (1546–1601). Tycho, as he is known, advanced the field by designing and constructing greatly improved astronomical instruments. Tycho led a remarkable life. Abducted in childhood by his childless uncle, he received the best possible education and rose to great fame. He first came into prominence in 1572 at the age of 27, when he discovered a new bright star—a supernova in the constellation Cassiopoea. King Frederick II of Denmark and Norway rewarded him by giving him title to an island between Denmark and Sweden, and building him a castle and observatory.

Tycho Brahe's improved instruments allowed him to test the predictions of both the Ptolemaic and Copernican systems. His newly designed instruments reduced observational errors by a factor of 20. He revealed discrepancies in the predictions of both the Ptolemaic and Copernican systems.

Upon his death, Tycho Brahe's data came into the hands of his mathematically gifted assistant, Johannes Kepler (1571–1630). Kepler had become Tycho's assistant in 1600, and he carried on the work of observation and analyses that his mentor had begun.

Kepler derived three empirical laws of planetary motion that provided a mathematical description of solar system orbits:

- Planetary orbits are elliptical with the Sun at one focus.

- An imaginary line from a planet to the Sun sweeps out equal areas in equal times.

- The square of a planet's orbital period (its "year") is proportional to the cube of its mean distance from the Sun.

These laws placed the Copernican model on a firm mathematical footing. In introducing these ideas, Kepler expressed his deep conviction that the universe holds a deep order. Yet, in spite of the mathematical logic and order that Kepler brought to the heavens, he still had to contend with a

superstitious world. In 1615 his elderly mother was jailed and brought to trial for witchcraft after being accused by a vindictive neighbor.

Galileo Galilei (1564–1642) transformed both the content and the methodology of science. He made major contributions to the fields of astronomy and physics, devised several ingenious practical inventions, and was a founder of experimental science. Galileo, son of a Florentine musician, began his schooling in medicine, but soon was drawn to mathematics and natural philosophy. He was a brilliant thinker, but could be tactless and arrogant, and thus made many enemies, both in academic circles and among the leading politicians of the day.

**Empirical mathematical laws describe motions in the heavens and on earth.**

Galileo pioneered the use of the telescope, which he used to reveal unanticipated "imperfections" in the heavens. His first observations were published in *The Starry Messenger* in 1610. Throughout the book, Galileo emphasizes the importance of modern observations over ancient authority. Galileo observed craters and mountains on the Moon, Saturn's rings, and sunspots, all of which challenged the prevailing view that celestial objects are perfect spheres. He documented numerous stars not visible to the unaided eye, thus undermining the authority of Aristotle and other ancient scholars. Galileo also observed four moons of Jupiter, which demonstrated that not all celestial objects orbit the Earth. His publication of these discoveries, and his bold support of the Copernican system in his *Dialogue Concerning Two World Systems* (1632), ultimately led to his famous and frequently oversimplified heresy trial in 1633.

To many scientists, Galileo is honored first and foremost as a founder of experimental science. He sought to understand the mathematical laws that describe falling objects—an important aspect of terrestrial mechanics. Aristotle said that heavier objects fall faster than lighter objects, a claim that Galileo demonstrated was false. Realizing that free-falling objects move too fast to measure with the observation techniques of his day, Galileo devised an ingenious adjustable ramp to "dilute" the effects of gravity. This is known as the "rolling ball" experiment, which demonstrates that the distance traveled by a falling body is proportional to the square of the time of the fall.

Galileo discovered that the horizontal motion of a falling object is independent of its vertical motion. He tested these ideas experimentally by firing cannonballs off of a cliff and observing the curving path of the fall. Galileo's empirical laws of terrestrial motions are not unlike those of Kepler for planetary motions. It remained for Isaac Newton to merge the empirical laws of Kepler and Galileo into one set of universal laws of forces and motions. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 2.

## Supplementary Reading

Andrade, *Sir Isaac Newton*, Chapters 1–2.

Caspar, *Kepler 1571–1630*.

Cohen, *Birth of a New Physics*, Chapters 4–6.

Drake, *Galileo: Pioneer Scientist*.

Harre, *Great Scientific Experiments*, Chapter 6.

Kuhn, *The Copernican Revolution*.

Zeilik, *Astronomy,* Chapters 2–4.

## Questions to Consider

**1.** Based on the discoveries of Kepler and Galileo, how would you characterize the role that mathematics plays in science? Is the correspondence between the geometrical abstraction of quadratic equations (including ellipsoids and parabolas) and motions in the natural world purely coincidental?

2. If you were to duplicate Galileo's rolling ball experiment today, how might you improve on his measurements of distance and time? (Assume an unlimited research budget.)

# Newton's Laws of Motion

## Lecture 5

**How astonishing then, that one set of mathematical laws formulated by Isaac Newton can be used to predict the motions of objects anywhere in the universe.**

By 1640, Johannes Kepler had derived the mathematical foundation for describing planetary orbits around the Sun, and Galileo Galilei had presented equations that predicted the behavior of falling objects. Yet, at that time, the studies of terrestrial and celestial mechanics remained separate domains, presumably with quite different sets of natural laws. It remained for Isaac Newton (1642–1726) to synthesize the empirical descriptions of celestial and terrestrial motions into one set of laws that applies to motions everywhere in the universe.

Newton was a student of mathematics and natural philosophy at Cambridge University, from which he graduated with a Bachelor's degree in 1665. In that same year, before he could return for further studies, the Great Plague struck England. With the University shut down, Newton spent 18 months at his family farm in intense personal study and thought. During that remarkable year and a half he formulated many of his major contributions to science, including the branches of mathematics now known as integral and differential calculus, many of the laws of optics, the universal laws of motion, and the law of gravitation! Newton returned to Cambridge University in 1667, and remained at Trinity College for the rest of his life.

**One set of mathematical laws, formulated by Isaac Newton, can be used to predict the motion of objects anywhere in the universe.**

In formulating his three laws of motion, Newton first divided all physical movement into one of two categories. Uniform motion is the movement displayed by objects traveling in one direction at a constant speed. Uniform motion includes the special case of an object at rest.

Previous scholars had also considered the circular orbits of planets a kind of uniform motion.

Newton classified orbital motions incorporating a change in direction, as well as any motion involving a change in speed, to fall in the second category of motion, known as acceleration. Acceleration includes both speeding up and slowing down. Acceleration also occurs any time direction is changed, whether or not the speed changes.

Newton's first law of motion states: "Every body continues in its state of rest, or of uniform motion in a [straight] line, unless it is compelled to change that state by forces impressed upon it." Objects can display three distinctive types of behavior:

- An object can move at constant speed and direction, varying in neither speed nor direction.

- An object can stand still.

- An object can accelerate under the influence of a net force.

The first law of motion provides an operational definition of "force" as the phenomenon that causes an object to accelerate. The idea that circular planetary orbits, as well as all other accelerations, are caused by an unbalanced force was radical in Newton's day, for it demanded that forces act over the huge distances of space.

Newton's second law of motion defines the exact mathematical relationship among three measurable physical quantities: force, mass, and acceleration. "The acceleration produced on a body by a force is proportional to the magnitude of the force and inversely proportional to the mass of the object." Because mass is measured in kilograms (kg) and acceleration is measured in meters per second per second (m/s2), the unit of force is the kg-m/s2, called the "Newton." Mass in this equation represents an object's tendency to resist acceleration—a property called its "inertia." The more massive an object, the greater the force necessary to impose a given acceleration, and thus the greater its inertia.

The third law of motion is the familiar but subtle statement: “For every action there is an equal and opposite reaction.” Forces always act simultaneously in precisely balanced pairs. If you apply a force in throwing a ball, the ball applies an equal and opposite force to your hand. Newton’s three laws of motion together provide a complete framework for investigating and understanding all of the forces and motions that occur in our lives. Newton, himself, applied this framework to describe the ever-present force of gravity. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 2.

## Supplementary Reading

Andrade, *Sir Isaac Newton*, Chapter 3.

Cohen, *The Birth of a New Physics*, Chapter 7.

## Questions to Consider

**1.** Identify specific ways in which Newton’s three laws of motion have come into play in your life during the past 5 minutes.

**2.** What forces besides gravity affect you in your daily life? In other words, what forces besides gravity cause objects to accelerate?

# Universal Gravitation

## Lecture 6

**Newton's analysis of the force of gravity was rooted in his understanding of the relationship between motion and force.**

Isaac Newton's three laws of motion define the concept of "force," a phenomenon that causes a mass to accelerate. Newton's laws establish the mathematical framework necessary for identifying and studying the behavior of any natural force. During 1665–1666, Newton's remarkable year of discovery, he deduced a mathematical description of the most pervasive of these forces—the universal force of gravity. To Newton's contemporaries, gravity was a terrestrial force, restricted to objects near the Earth's surface. Newton's great advance was to realize that one force—the universal force of gravity—acted on both an apple and the Moon.

The apple, attracted to the Earth by gravity, falls straight down. If the apple is thrown, it follows a parabolic path back to the surface, in accord with the observations of Galileo. If the apple is launched with sufficient acceleration, it will adopt an elliptical orbit, as observed by Kepler for the Moon and planets.

**Gravity is an attractive force that exists between any two masses, anywhere in the universe.**

Newton's investigations focused on finding a mathematical description of this force that would lead to the elliptical planetary orbits described by Kepler, as well as the law of falling bodies and the parabolic paths of cannonballs described by Galileo. Newton's universal law of gravitation defines the relationships among four measurable physical quantities: the mass of two objects, the distance between them, and the gravitational force thus generated:

$F = G \times [m_1 \times m_2]/d^2$ where G is the gravitational constant. Between any two objects there exists an attractive force of gravity that is proportional to the product of their masses, divided by the distance between them squared.

Newton's equation reveals that an equal gravitational force is experienced by any two objects—you and the Earth, for example, or the Earth and the Moon. Newton's equation for gravity has intuitive power. Gravity, in some deep and as yet mysterious way, is an attribute of mass. As the distance between two objects increases, the gravitational force between them drops off as one over the square of the distance—an "inverse square" relationship that is common in many everyday situations. This behavior suggests that we can imagine a gravitational field of lines radiating out from every mass.

The numerical value of the gravitational constant, G, is the key to determining the Earth's mass and, by extension, the mass of other heavenly objects. Henry Cavendish (1731–1810), a chemist and physicist at Oxford University, devised an ingenious torsion balance to measure G in 1798. He suspended a dumbbell with lead spheres from a wire such that the two suspended spheres were in proximity to two larger, fixed lead spheres. The slight force of gravity between the two pairs of spheres caused a measurable torsional force on the wire. In 1998, an international group of scientists met to observe the bicentennial of Cavendish's discovery and to review new experiments devised to determine the value of G, now said to be $6.674 \times 10^{-11} m^3/kg/sec^2$.

Newton's law of gravitation can be used to calculate many useful things. First, it is important to distinguish between weight and mass—two terms that are often interchanged. Weight is the gravitational force exerted by an object. Weight varies from place to place, depending on the strength of the gravitational field. Mass is the amount of stuff (measured in kilograms) of which an object is made; mass is invariant from place to place. Objects weigh less on the Moon because the mass and the radius for the Moon are different than for Earth.

Newton's universal laws of motion and gravity revealed a deep, pervasive order to the natural world. One set of laws applies both at the Earth's surface and in the heavens, and these laws provide a framework by which many other phenomena can be studied. Perhaps Newton's greatest legacy is a view of the universe as a place of deep mathematical order—a clockwork universe, whose mechanisms can be deduced through observation and analysis. This optimistic view was adopted in other human pursuits, including economics

and politics during the Enlightenment a century later. Some followers of Newton, notably the French mathematician Pierre Simon Laplace (1749–1827), even speculated that, since the laws of motion are exact and each particle in the universe has a measurable position and velocity, the future is preordained. Some scholars even called into question the nature of free will. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 2.

## Supplementary Reading

Andrade, *Sir Isaac Newton*, Chapters 3–5.

Cohen, *The Birth of a New Physics*, Chapter 7.

## Questions to Consider

1. If gravity is always an attractive force between any two objects, why does a helium balloon fall up? (Hint: Think about Newton's laws of motion.)

2. When a space ship accelerates in the vacuum of space, what does it push against?

# The Nature of Energy

## Lecture 7

**Newton's laws provided the scientific world with a remarkable ability to study forces and motions in nature as well as an unswerving confidence that various other laws could be deduced by observing that natural world. But Newton was not able to solve the riddle of heat and its companion phenomenon—light, which baffled researchers well into the 19th century. This lecture is going to explore the nature of energy, which is defined as the ability to do work.**

The study of energy is called thermodynamics. Unlike Newton's laws of motion, the laws of thermodynamics did not spring fully formed from one mind. Rather, these ideas emerged gradually from the work of many researchers, and it was only later that they were set down in the form we now know. Consider two age-old questions: What is heat? And what is light? Even though heat and light are among the most tangible of all physical phenomena, their origins are among the most subtle and difficult to deduce. Their understanding arose from the abstract concept of energy.

The definition of energy requires the new concept, work, which has a very specific meaning in physics. Work is expended when a force causes a body to move through a distance: work equals force times distance. The unit of work is the joule, defined as a force of one newton exerted over a distance of one meter (a newton-meter). In the English system, the associated unit of work is the foot-pound. Energy is the ability to do work–the ability to exert a force over a distance. Energy is a measurable attribute of physical systems but, unlike mass or motion, it has an intangible quality.

**Energy is the ability to do work.**

Energy was difficult to recognize and describe, in part because it can adopt so many different forms. There are many ways to exert a force over a distance. Even so, three forms of energy–kinetic, potential, and waves–have long been recognized for their ability to do work. The most obvious form of energy is

carried by objects in motion–kinetic energy. The kinetic energy of any object can be calculated from its mass and velocity. force equals one-half of the mass times the velocity squared or: F=(½)(mv2)]. This equation allows us to calculate the relative energy of a car traveling at different speeds.

Many natural systems store energy, called potential energy. The most obvious form of potential energy is due to gravity—the stored energy of water behind a dam or the weight of a grandfather clock. Other common forms of potential energy are chemical energy (in gasoline and food), electrical potential (in batteries and your wall outlets), magnetic potential (in a refrigerator magnet), and elastic potential (in a tightly stretched rubber band).

Waves represent an efficient form of kinetic energy, in which energy can be moved long distances with only small movements of mass. Sound waves transmit energy in the air. Waves at the surface of the ocean can carry energy across thousands of miles. Earthquakes can transfer immense amounts of energy and cause devastation to inhabited areas.

It took much longer to discover three additional, far more subtle forms of energy: heat, light, and mass. The nature of heat was a matter of intense debate for centuries. Many noted scientists, including the influential French chemist Antoine Lavoisier (1743–1794), favored the caloric theory, which described heat as a massless fluid that could flow from object to object.

The debate was ultimately resolved by the opportunistic American-born inventor, Benjamin Thompson (1752–1814), known as Count Rumford. Rumford had always been fascinated by the phenomenon of heat, and he conducted many studies to improve its use in everyday life. His invention of the modern style cookstove and fireplace gained him fame and a degree of wealth. Rumford was appointed commandant of police in Bavaria, where one of his duties was to oversee the manufacture of cannons. Rumford noted the unremarkable fact that boring cannon produced heat. Rumford realized that the heat was produced by friction—mechanical action.

The caloric theory was buried forever when British scientist Humphry Davy, a brilliant public lecturer, succeeded in melting ice just by rubbing two pieces together on a cold winter day.

Another form of energy is radiation–light traveling 186,000 miles per second. The principal source of energy at the Earth's surface is radiation from the Sun, which travels across the vacuum of space.

Finally, one of the defining discoveries of modern science was Albert Einstein's recognition in 1905 that mass is also a form of energy, according to the familiar equation, E = mc2, where c is the speed of light. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 3.

## Supplementary Reading

von Baeyer, *Maxwell's Demon*, Chapters 1–2.

## Questions to Consider

1. Work and energy are both measured in the unit joules–a force times a distance. Does that mean that work and energy are the same thing? How are these two physical concepts related?

2. Is it possible that there are as yet undiscovered forms of energy? What might be the implications of such a new form?

# The First Law of Thermodynamics

## Lecture 8

**It took scientists centuries of studying heat and light and various mechanical processes before the basic definition of energy—the ability to do work—emerged. Once that concept was formulated, however, the systematic behavior of energy, the science of thermodynamics advanced quite rapidly.**

Scientists hold a firm belief that the universe possesses deep order. An extension of this conviction holds that matter is neither created nor destroyed. Once the many forms of energy were catalogued, scientists wondered whether energy, too, might be conserved. As an illustration of nature's myriad energy transfers, we can follow the chain of energy of everyday events.

Riding a roller coaster provides a classic example. An electric motor converts electrical potential energy into gravitational potential energy as the coaster slowly climbs the first hill. As the coaster crests that hill and starts its downward plunge, gravitational potential is converted to kinetic energy, and so on. Your car stores chemical energy in the form of gasoline, which represents ancient energy from the Sun. That energy eventually becomes kinetic energy of the car and heat in the engine. One of the greatest challenges in modern technology is to find cheap and efficient ways to convert one form of energy into another.

**Energy may change forms many times, but the total amount of energy in a closed system is constant.**

The first law of thermodynamics states that the total amount of energy in a closed system is constant. Nevertheless, it was difficult to demonstrate because it is difficult to devise a closed system. The first universally convincing demonstration of the first law was an elegant experiment devised by the English brewer and sometime physicist James Prescott Joule, who is honored today by the unit of energy, the joule. Joule agitated water with a paddle

wheel, which was turned by a clever linkage to a descending pair of heavy weights. He then compared the gravitational energy released by the weights' descent to the increase in water temperature. This phenomenon also occurs in a waterfall; the higher the waterfall, the greater the heating. The first law of thermodynamics allows the precise mathematical description of energy transfer events.

The first law of thermodynamics says nothing about how fast energy is transferred. A candle and a firecracker may store the same amount of chemical potential energy, but the two objects behave very differently when lit.

The rate of energy release, called power, is defined as energy divided by time. The standard unit of power is the watt, which equals one joule per second. The watt is named after Scottish inventor James Watt (1736–1819), who contributed to improvements in the Newcomen steam engine and who coined the term "horsepower." The concept of power comes forcefully into play in sports. Winners are often determined by how fast energy is released.

Energy is a pervasive theme in science, and every subdiscipline must incorporate the concept. Consequently, a bewildering number of energy units have been devised. Home energy bills in the United States most commonly use kilowatt-hours for electricity, therms for natural gas, and gallons for heating oil. The English system employs the foot-pound or the horsepower-hour (about 2 million times larger). Physicists use joules or ergs (one millionth of a joule) for everyday objects and events but resort to electron volts when dealing with atomic-scale processes. Chemists often use calories in everyday chemical reactions, but they resort to a number of other units, such as the reciprocal centimeter, in special cases.

To many scientists, the first law carries a profound significance about the underlying symmetry of the natural order. To Joule, the first law was nothing less than proof of the beneficence of the Creator. Others saw in the conservation of energy a natural law analogous to the immortality of the soul. British physicist William Thompson (1824–1907), known as Lord Kelvin, was drawn to the perfection of the conservation of energy, and was equally repelled by Darwin's theory of evolution, in which random variations

and chance play a central role. Kelvin used the first law as a refutation of Darwin's ideas.

Every closed system, such as the Earth and the Sun, has a fixed budget of energy. For life to exist on Earth, the Sun must expend that energy at a prodigious rate. Making a few simple assumptions about all known sources of energy available to the Sun, Kelvin estimated that life on Earth must be significantly less than 100 million years old—much less than the hundreds of millions of years required for Darwinian evolution. Kelvin's reputation as a physicist was so great, and the laws of physics were so unshakable, that his pronouncement was for almost half a century the major hurdle for acceptance of Darwin's theory. The conflict was resolved in 1904 when Ernest Rutherford announced the discovery of a powerful new energy source, radioactivity—a manifestation of nuclear energy. The first law provided a framework for investigating energy, but, as we shall see in the next lecture, it's only half the story. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approac*h, Chapter 3.

## Supplementary Reading

Burchfield, *Lord Kelvin and the Age of the Earth*.

von Baeyer, *Maxwell's Demon*, Chapters 1–3.

## Questions to Consider

1. Trace the chain of energy that allowed you to exert a force, to push a button, to start this lecture.

2. Would your life be noticeably different if a small fraction of energy vanished after every energy transfer, instead of being conserved? Why do you think scientists feel so strongly about the "truth" of the first law of thermodynamics?

# The Second Law of Thermodynamics

## Lecture 9

**The first law of thermodynamics is wonderful news. You can change energy from one form to another and to another as many times as you want to, and the total amount of energy is constant. Energy is conserved. But nature hasn't given us a completely free ride in this regard. The second law of thermodynamics places severe restrictions on how energy can be used, how it can transfer from one form to another.**

In everyday life we experience many limitations on energy transfers. A hot bowl of soup becomes cooler, for example, but a cool bowl of soup never spontaneously heats up. A second law of thermodynamics is required. The most intuitive statement of the second law of thermodynamics is that heat tends to diffuse evenly: heat flows from hot to cold. This statement incorporates two related but different concepts—heat versus temperature. Heat is a quantity of energy (joules, calories, etc.). The quantity of heat energy thus depends directly on the amount of material the system contains.

Temperature is a relative term: Two objects are at the same temperature if no heat energy flows spontaneously from one object to the other. Every temperature scale requires two reproducible reference points. At absolute zero, −273.15ºC, the kinetic energy of atoms and molecules is zero.

**Heat has a universal tendency to dissipate.**

A consideration of heat versus temperature leads us to another important property of materials—the heat capacity. Every material has the capacity to store heat energy, but some substances do this better than others. Think about placing a pound of copper and a pound of water on identical burners. Which one heats up more quickly? Heat capacity is the amount of heat energy that a substance can hold. Water has a much higher heat capacity than copper. A useful measure of the heat capacity is called "specific heat," the energy required to raise the temperature of 1 gram by 1ºC. For water, this amount of energy is defined as the calorie. By contrast, it takes only 0.1 calorie to raise a gram of copper by a degree.

The second law of thermodynamics depends on the motion of heat. Heat can move by three different mechanisms: conduction, convection, and radiation. Conduction is the transfer of heat from atom to atom in a solid object. It is the transfer of heat through a moving fluid, either a liquid or a gas. Radiation is the transfer of heat by a form of light that travels 186,000 miles per second.

Insulation in animals, in clothing, and in houses is designed to reduce the inevitable transfer of heat. Most heat loss comes from convection. Fur and fiberglass insulation trap pockets of air so small that convection can't occur. Thermos bottles carry this strategy a step further by having a vacuum barrier, across which neither conduction nor convection can occur.

The second law of thermodynamics applies to so many physical situations that there are a number of very different ways to express the same fundamental principle. A second, more subtle statement of the second law is that an engine cannot be designed that converts heat energy completely to useful work. Thermodynamics were of immense importance to designers of steam engines, so many theoretical insights came from this practical device. The French military engineer Nicolas Sadi Carnot (1796–1832) came the closest to deriving the second law from a study of work and heat.

Carnot considered two sides of the relationship between work and heat. He recognized that work can be converted to heat energy with 100% efficiency. It is possible to convert the gravitational potential of an elevated object, or the chemical potential of a lump of coal, completely to heat without any loss. Converting heat to work is more restricted. Inevitably, some heat winds up heating the engine and escaping into the surroundings. You can expend work to raise water and fill a reservoir; with care, without losing a drop. But if water is released to produce work, some of the water has to flow through the system.

Carnot's great contribution was the derivation of the exact mathematical law for the maximum possible efficiency of any engine—that is the percentage of the heat energy that can actually do work. The maximum efficiency of an engine depends on two temperatures: $T_{hot}$, the temperature of the hot reservoir (burning coal, for example), and $T_{cold}$, the temperature of the cold reservoir of the surroundings into which heat must flow (usually the air or

cooling water). An engine is a mechanical device imposed between two heat reservoirs. In this sense, an engine is any system that uses heat to do work—the Sun, the Earth, your body, or a steam engine. Efficiency of an engine can be expressed by the formula

$$\text{Efficiency} = \frac{T_{hot} - T_{cold}}{T_{hot}} \times 100$$

In Carnot's day, before these principles were understood, typical steam engine efficiencies were 6%. Today, improved insulation and cooling have raised efficiencies of coal-burning power plants to 40%, which is close to 90% of the theoretical limit. Carnot's equation illustrates why fossil fuels—coal, gas, and oil—are so valuable. These carbon-rich fuels burn with an extremely hot flame, thus elevating the temperature of the hot reservoir and increasing the maximum efficiency. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 4.

## Supplementary Reading

Atkins, *The Second Law*.

von Baeyer, *Maxwell's Demon*, Chapters 5–17.

## Questions to Consider

**1.** Identify three examples of the second law of thermodynamics that are occurring where you are, right now. Can you think of any physical event where the second law does not come into play?

**2.** If engines operate more efficiently in colder surroundings, why don't we build all our power plants in the Arctic, to minimize Tcold? (There may be several reasons.)

# Entropy

## Lecture 10

**As scientists of the 19th century thought about the implications of energy, they eventually came to a startling realization—the great principle that every isolated system becomes more disordered with time. In this lecture … I'm going to introduce the concept of entropy—the tendency of systems to become messier quite spontaneously, in spite of everything we do.**

The discussion of the second law of thermodynamics thus far has focused on the behavior of heat energy: Heat flows spontaneously from warmer to cooler objects, and an engine cannot be 100% efficient. As useful as these ideas may be, the second law reaches far beyond the concept of heat. In its most general form, the second law comments on the state of order of the universe.

All systems in the universe have a general tendency to become more disordered with time. Many experiments can be designed to study this phenomenon. Shuffle a fully ordered deck of cards and it becomes disordered—never the other way around. Shake a jar of layered colored marbles and they become mixed up—never the other way around. These examples are analogous to a situation where a hotter and colder object come into contact. The heat energy of the hotter material gradually spreads out. In each of these cases the original state of order could be recovered, but it would take time and energy.

The concept of entropy was introduced in 1865 by the German physicist Rudolf Clausius (1822–1888) to quantify this tendency of natural systems to become more disordered. Clausius synthesized the ideas of Carnot, Joule, and others and published the first clear statement of the two laws of thermodynamics in 1850. The second law, however, was not presented in a rigorous mathematical form. Clausius realized that for the second law to be quantitatively useful, it demanded a new, rather abstract physical variable—entropy. He defined entropy purely in terms of heat and temperature: entropy is the ratio of heat energy over temperature. Clausius observed the behavior of steam engines and realized that this ratio must either remain constant or increase—that is,

the heat divided by the temperature of the cold reservoir is always greater than or equal to the heat divided by the temperature of the hot reservoir (or heat divided by work). Thus the entropy of a system does not decrease. One can summarize the two laws of thermodynamics as energy is constant (first law), but entropy tends to increase (second law).

A more intuitive approach to entropy is obtained by thinking about heat energy as the kinetic energy of vibrating atoms. Heat spreads out because faster atoms with more kinetic energy collide with slower atoms; eventually, the kinetic energy averages out. Ultimately, the order of any system can be measured by the orderly arrangement of its smallest parts—its atoms. A crystal of table salt with regularly repeating patterns of sodium and chlorine atoms is highly ordered. A lump of coal, similarly, has an ordered distribution of energy-rich carbon-carbon bonds. Dissolve the salt in water or burn the coal and energy is released, while the atoms' disorder—their entropy—increases.

**Every isolated system becomes more disordered with time.**

The "arrangement" of atoms can also refer to the distribution of velocities of particles in a gas—i.e., its temperature. Imagine what happens when two reservoirs of gas at different temperatures are mixed. Temperature averages out and the entropy—the randomness—increases. This definition of entropy was placed on a firm quantitative footing in the late 19th century by the German physicist, Ludwig Boltzmann (1844–1906). Boltzmann used probability theory to demonstrate that, for any given configuration of atoms, entropy is related to the number of possible ways you can achieve that configuration. The most probable arrangement is observed. Entropy is the microscopic manifestation of probability.

The second law of thermodynamics has far-reaching consequences. One consequence of the second law of thermodynamics is that heat in the universe must eventually spread out evenly. Life on Earth is possible because the Sun provides a steady source of energy, and the Earth holds a vast reservoir of interior heat. In the 1890s, many scholars addressed the concept of the "heat death" of the universe.

The second law of thermodynamics provides us with tantalizing insights about the nature of time. Imagine playing a favorite movie backwards. Some forms of motion, such as a ball flying through the air, seem completely reversible. Other images are obviously impossible in the real world. The tendency of a system's entropy to increase defines the arrow of time.

Living things must obey the laws of thermodynamics, which come directly into play with the concept of trophic levels. Every organism must compete for a limited supply of energy. Plants, in the first trophic level, get their energy directly from the Sun. Herbivores, the second trophic level, obtain energy from plants, but about 90% of the plant's chemical energy is lost in the process. The second law of thermodynamics helps to explain why large carnivores—lions and killer whales, for example—are relatively rare.

The second law of thermodynamics is often invoked by creationists to prove that life could not have evolved from nonlife. Living things are exceptionally ordered states. Such an unimaginably ordered system could not possibly arise spontaneously. Locally ordered states arise all the time. Every time a plant grows, new highly ordered cells are formed.

One question that science has not yet fully addressed is the tendency for highly ordered complex states, such as life, to arise locally. Perhaps, someday, there will be another law of thermodynamics. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 4.

## Supplementary Reading

Morris, *Time's Arrow*.

von Baeyer, *Maxwell's Demon*, Chapters 5–17.

## Questions to Consider

1. Is it impossible for a disordered system to become ordered spontaneously? Would such an event violate the second law of thermodynamics?

2. The number of different arrangements of 52 cards in a deck is approximately 8 followed by 67 zeros! Each of these possible arrangements is a unique sequence, so why do we think of certain arrangements as more ordered than others? (Hint: For any given sequence, how much information is required to describe the arrangement of the 52 cards?)

# Magnetism and Static Electricity

## Lecture 11

**I'm going to tell you about two of the most ubiquitous yet complex phenomena in nature in our daily lives—that is magnetism and static electricity. One of the great and surprising principles of science is that magnetism and static electricity are forces that can be either attractive of repulsive.**

One of the most important and mysterious forces in Newton's day was magnetism, which causes one end of an iron needle to accelerate in the direction of the Earth's North Pole. The study of magnetism was important in an age of ocean exploration and commerce. Magnetic rocks were discovered by the ancient Greeks in a region of Asia Minor called "Magnesia." These rocks attract pieces of iron, and they attract or repel each other. Ancient scholars knew that a magnet suspended by a string will pivot so that one end (the north pole) points north, and the other end points south. A compass is a magnetic needle on a pivot. When two magnets are brought together, opposite poles attract and like poles repel. A piece of unmagnetized iron can be magnetized by repeated stroking of a magnet.

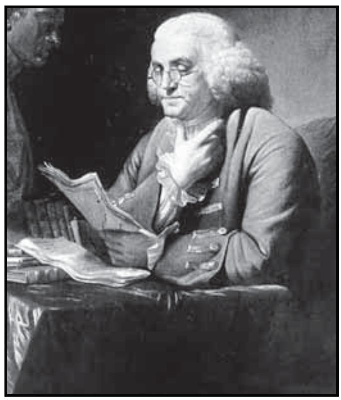
**Magnetism and static electricity are forces that can be either attractive or repulsive.**

Compass makers, such as British sailor and instrument maker Robert Norman (c.1550–1600), attempted to improve the sea-going compass. His principal work, *The Newe Attractive* (1581), described the tendency of compass needles to dip. Dip was a nuisance to compass makers, because it was difficult to get their needles to balance properly. To study the effect of dip, Norman pivoted a compass needle on a horizontal axis and thus established the angle of dip. Norman devised an ingenious experiment to test whether there is a net force on a magnetic needle.

Various ideas about the behavior of magnets were synthesized in the research of English physician and physicist William Gilbert (1544–1603). In *De Magnete* (1600), Gilbert demonstrated that every magnet has two poles;

broken fragments of a magnet are themselves complete magnets. Gilbert proposed that the Earth, itself, is a giant magnet with its own field and that smaller magnets, such as compass needles, align themselves in this field. This kind of field, with a north and south pole, is called a dipole. The Earth, the Sun, and many other bodies are large dipole magnets. Some volcanic rocks "freeze in" the orientation of the Earth's magnetic field when they cool. British experimentalist, Michael Faraday (1791–1867), performed the simple demonstration of sprinkling iron filings near a magnet.

Static electricity is a subtle, yet pervasive, force. In the 18th and early 19th centuries, static electricity was a curiosity, of little practical concern, but still worthy of investigation. William Gilbert, who studied the Earth's magnetic field, also studied electrostatics. He found that some substances become electrically "charged" when rubbed with fur or silk—amber, glass, and some minerals, for example. Some materials, called insulators, hold this charge. Conductors, especially metals, do not hold their own charge, and they drain charge away from insulators. Charges can be passed from one object to another by touching. Electric friction machines, in which a belt of rubber, cloth, or fur is rapidly spun over a piece of amber or other insulating solid, are able to develop large charges. Such machines were used well into the 20th century to produce extremely high voltages in physics experiments.



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**Benjamin Franklin, an early theorist about the nature of electricity.**

Electrically charged objects exert forces on each other—forces that can be measured systematically by suspending balls of styrofoam on threads. Two electrically charged objects can either attract or repel each other, similar to a magnet. Benjamin Franklin (1706–1790), American statesman and signer of both the Declaration of Independence and Constitution, devised an explanation for these curious observations. Franklin suggested that electric charge is a fluid (what we now know as electrons) and that all uncharged substances have some fixed amount of this fluid. A

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**Franklin's famous kite experiment, June 1752.**

material becomes charged when friction adds or removes charges. If it has too many electrons, it has a negative charge; if too few electrons, it has a positive charge. The behavior of these balls can be explained if like charges repel and opposite charges attract. The behavior of Franklin's electrical fluid modeled all observed electrostatic behavior long before the discovery of electrons. Franklin applied his knowledge in his invention of the metal lightning rod, which conducts electrical fluid harmlessly into the ground.

Charles Coulomb (1736–1806) conducted meticulous experiments on the electrostatic force and determined the exact force law between two charged objects: force equals the product of the two charges divided by the square of the distance between them, times an appropriate constant. This equation looks very much like the equation for gravity. The law for electrostatic force is different from gravity in two important ways: the electrostatic force may be either attractive or repulsive, whereas gravity is always attractive, and the electrostatic force is vastly greater than gravity.

Static electricity is not a central topic of physical research these days, but we do have to deal with its consequences. Lightning occurs when violently agitated raindrops in a cloud pick up an electric charge through friction. A xerography machine uses static electricity to apply black plastic powder to paper. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 5.

## Supplementary Reading

Harre, *Great Scientific Experiments*, Chapter 3.

## Questions to Consider

1. If the Earth had no magnetic field, how might the force of magnetism have been discovered? Would scientists have thought it worth studying?

2. Why are effects of static electricity so much more noticeable on cold, dry days?

# Electricity

## Lecture 12

**First, I'm going to tell you about the surprising history of the invention of the battery, which was invented in Italy more than 200 years ago. Then we're going to look at the design of electrical circuits and their principle components—that is, a source of energy, a device that does something interesting or useful, and finally a closed loop of conducting material, usually wired, and completes that circuit.**

Static electricity is limited in its practical applications. Most modern uses of electricity rely on electrons that move. Newton's first law of motion demands that electrons can't move unless a force is applied. A method for applying such a force was discovered in 1794, when the Italian physicist Alessandro Volta (1745–1827) invented the battery. Alessandro Giuseppe Antonio Anastasio Volta was the fifth of five sons born to an impoverished family of lesser nobility in northern Italy. He showed a flair for foreign languages and began experimental studies on electricity while still a teenager. He spent his career as professor of physics at the University of Pavia.

Volta's most important contributions followed discoveries of his countryman, the anatomist Luigi Galvani (1737–1798), who focused much of his work on the subject of animal electricity. Galvani studied the effects of electric sparks, which caused the muscular legs of dead frogs to twitch and convulse. While performing these experiments he noticed the leg would twitch when touched simultaneously by a brass wire and a steel scalpel. Further experiments clarified this phenomenon. Galvani showed that when copper and iron wires were inserted into different parts of a dead frog's legs, and these two wires were then touched together, the legs would convulse. The anatomist Galvani interpreted this phenomenon in terms of "animal electricity," an electricity intrinsic to biological tissues.

The physicist Volta directed his attention to these phenomena, focusing more on the metallic elements of Galvani's experiment than the biological components. He soon became convinced that the juxtaposition of two

different metals led to the observed electrical phenomena, which he called "metallic electricity." He found that different pairs of metal produced different degrees of effect. A feud developed between supporters of Galvani's animal electricity and Volta's metallic electricity.

Volta's view soon prevailed because his electrical effects could be produced independently of frog's legs or other biological material. Electrical potential is analogous to the gravitational potential of water behind a dam. For Volta, the next step was to devise various arrangements by which different metals were placed in contact. He found that he could produce electricity just by stacking alternating plates of metals, such as silver and zinc, in a saltwater bath. Volta's battery marked a turning point in electrical science. For the first time, researchers could rely on a steady source of electricity, rather than transient sparks and discharges.

Volta's battery and its successors proved invaluable in chemical experiments. Within weeks of its announcement, the British chemists William Nicholson and Anthony Carlisle built a crude battery, and they used it to decompose water into hydrogen and oxygen for the first time. Batteries were used to decompose other substances, leading to the discovery of several new elements. Larger batteries were built with more pairs of metal plates. The flamboyant English chemist and science lecturer Humphry Davy constructed a mammoth battery with 2000 double plates at the Royal Institution. In 1810, he became the first person to demonstrate electric lighting when he vaporized charcoal, platinum, and other materials in blinding incandescent displays.

**Electric currents are produced by moving electrons in a closed path.**

The battery introduced a new field of research on electric currents and electric circuits. An electric circuit incorporates three components: a source of electrical energy, a device that responds to this electrical potential, and a closed loop of conducting material. The source of electrical energy might be a battery, a solar cell, or a hydroelectric plant. An electrical device is an object or substance that responds in some interesting or useful way to the voltage of the source. A piece of wire or other conducting material is required to close the loop of an electric circuit.

Electrical circuits can be quantified in several useful and important ways. The flow of electrons through a circuit is called an electric current, measured in amperes. The electrical potential that causes electrons to move is measured in volts, in honor of Volta. Every circuit has some resistance to the flow of electrons, measured in ohms. Power is defined as work divided by time. In an electrical circuit, power is the current times the voltage and is measured in watts.

In homes, the energy source is typically a power plant many miles away. The separate circuits in your home that feed off this power network are of two types. Series circuits have several devices, each linked up after the next in a single large loop. The same current flows through every device. Parallel circuits are arranged so that a single source supplies voltage to separate loops, each dedicated to one device. Every device sees the same voltage, but different currents. Kirchhoff's Laws systematize the behavior of circuits. The first law is a restatement of the law of energy conservation: energy produced by the source equals the energy consumed in the circuit (including heat energy of resistance). The second law is a statement of conservation of current: the current flowing into any junction equals the sum of the currents flowing out. Since current is simply the number of electrons flowing past a point, this law is equivalent to saying that electrons are conserved.

The word electricity has been introduced in many different contexts: animal electricity, metallic electricity, static electricity, lightning, and so forth. British physicist Michael Faraday (1791–1867) showed that all forms produce the same effects, and thus unified the many faces of electricity. The unification of electricity with the seemingly unrelated force of magnetism transformed the world's technology. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 5.

## Supplementary Reading

Amdahl, *There Are No Electrons*.

Dibner, *Alessandro Volta and the Electric Battery*.

Harre, *Great Scientific Experiments*, Chapter 18.

Pera, *The Ambiguous Frog: The Galvani-Volta Controversy on Animal Electricity*.

## Questions to Consider

1. To what extent did the differing conclusions of Galvani and Volta regarding the twitching of frog's legs reflect their different scientific specialties?

2. Electricity is often described in terms of an analogy to a plumbing system. What are electrical analogues to pumps, pipes, water pressure, flow rate, and an obstruction in a pipe?

# The Joy of Science (Lectures 13–24)



**Scope:**

The great principles of science often reveal surprising connections between seemingly unrelated phenomena. Newton's laws of motion and gravity, for example, unified the supposedly separate domains of terrestrial and celestial motions. Similarly, the first law of thermodynamics established the equivalence of such disparate phenomena as heat, motion, light, and mass, all of which are forms of energy. In Part II of this lecture series we begin with another great unification—electricity and magnetism. The discovery that electricity produces magnetic fields and moving magnets produce electricity (Lecture 13) led to a unified description of electromagnetism by James Clerk Maxwell, and his subsequent discovery of the nature of light, or electromagnetic radiation (Lectures 14 and 15). Albert Einstein, building on Maxwell's discovery, developed his theory of relativity (Lecture 16) by assuming that observers experience the same natural laws no matter what their frames of reference. The constant speed of light implies that time must be relative to an observer's reference frame.

Shifting focus to the nature of matter, we next explore the atomic theory (Lecture 17) and the growing observational evidence that matter is made of elemental blocks. The atom consists of a massive, positively charged nucleus that is orbited by negatively charged electrons. According to the atomic model proposed by Niels Bohr (Lecture 18), electrons adopt specific energy levels. Movement from one energy level to another is called a quantum jump, and results in the absorption or emission of a photon—a quantum of light. These ideas are central to quantum mechanics (Lecture 19), which is based on the nonintuitive concept that at the subatomic scale every measurable quantity comes in discrete increments.

Dimitri Mendeleev unified the many different kinds of atoms into the periodic table of the elements (Lecture 20). Atoms link together in chemical bonds (Lecture 21) by the rearrangement of electrons; the bonding of carbon is especially varied and forms the basis of the field of organic chemistry

(Lecture 22). Materials of the physical world occur in several different states—solids, liquids, gases, and plasma—and they undergo a rich variety of phase transitions and chemical reactions (Lectures 23 and 24). ■

# Electromagnetism

## Lecture 13

**The connection between magnetism and electricity came in two steps. … The first is the discovery that electricity can produce magnetic fields—the principle of the electromagnet. Then it follows the symmetrical idea that moving magnets can produce electricity; that's the principle of the electric generator.**

The beginning of electricity's modern era can be traced to a small Danish classroom in 1820. There, in front of a room full of physics students, Hans Christian Oersted (1777–1851) discovered that electricity can produce magnetic fields. Oersted was the son of a Danish pharmacist, and he had planned to follow his father's profession, but he became captivated by electrical studies in 1800. He gained great popularity as a science lecturer and was given a professorship at the University of Copenhagen in 1806.

In 1820, Oersted hooked up a coil of wire to a battery and passed a current through the coil. He observed that a compass needle next to the coil moved whenever the circuit was closed. Prior to Oersted, electricity and magnetism were viewed as two separate phenomena, involving very different kinds of physical conditions. Oersted's work unified the study of electromagnetism.

Oersted's discovery led to a number of important inventions, because it provided a way to convert electrical potential energy into magnetic and kinetic energy. The electromagnet was the first application of this effect. In a buzzer, for example, a flexible magnetic piece, acting as a switch, repeatedly hits a metal plate as the circuit opens and closes. This principle is used in the telegraph. Electric motors use electromagnets to develop a magnetic push-pull between a rotor and its casing.

Scientists expect the physical world to display order and symmetry. Since moving electricity induces a magnetic field, then moving magnets should induce electricity. This effect was demonstrated by the British physicist

Michael Faraday (1791–1867) in 1831. Faraday, the son of a blacksmith, was apprenticed to a London bookseller. Faraday began to read and became entranced by science. After attending a public lecture series by the famous Humphry Davy, Faraday transcribed his lecture notes, bound them beautifully, and presented them to Davy as his calling card. He was soon employed as Davy's assistant, and he flowered into a distinguished scientist. In his famous experiment, Faraday attached one coil of wire to a battery, thus creating a magnetic field. Next to this coil he placed a second coil of wire in a circuit. Even though the second coil was not attached to any source, a strong current flowed. Faraday concluded that the magnetic field produced by the first circuit induced the current in the second circuit—the phenomenon of electromagnetic induction.

The demonstration that moving magnets can induce electricity in a coil of wire immediately suggested a new procedure for generating electric power. Place a coil of wire between two magnets and spin the coil; electricity will result. This device is called an electric generator or dynamo. This kind of power plant produces an alternating current (AC). This current differs from the direct current (DC) that is produced by a battery.

**Electricity and magnetism are two aspects of the same force.**

The symmetric interplay between electricity and magnetism comes into play in many ways. The electric motor, with its coils pushed into rotation by the electrical current, is the mirror image of the generator, with rotating coils inducing an electric current. Every telephone uses the symmetry of microphones and speakers. In every television and computer monitor, electromagnets control the image on the screen.

Revisiting the first law of thermodynamics, remember that energy can change from one form to another—from kinetic to potential, for example, or potential to heat. The technological importance of electromagnetic induction is that it provides an easy way to achieve previously difficult conversions. Prior to electricity, people had to build their industries next to the source of energy, but electrical energy can be transferred for many miles over wires.

The connections between electricity and magnetism were set down in an elegant mathematical form in the 1860s. The Scottish physicist James Clerk Maxwell (1831–1879) presented four equations that codified every aspect of electromagnetism. Though mathematically complex, the four equations can be described in words.

- A force exists between any two electrically charged objects; the force is proportional to the two charges and inversely proportional to the square of the distance between them.

- Magnetic poles always occur in pairs.

- Changing electric fields produces a magnetic field.

- Changing magnetic fields produces an electric field.

Equations can be manipulated by algebra to reveal sometimes hidden consequences. Maxwell manipulated his four equations and found that one possible mathematical solution was in the form of a wave of electromagnetism. Furthermore, from the quantities that appeared in his equations, the speed of these electromagnetic waves had to be 186,000 miles per second—the speed of light. Thus from esoteric experiments on magnets and static electricity arose not only the modern electrical age but also the solution to one of the oldest scientific mysteries—the nature of light. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 5.

## Supplementary Reading

Everitt, *James Clerk Maxwell: Physicist and Natural Philosopher*.

## Questions to Consider

1. Electric currents produce magnetic fields only if the wires curve. Is it possible to design a circuit without a magnetic field? How might an induced magnetic field be minimized?

2. Your car has both an electric generator and a battery. Do your lights and radio operate on AC or DC?

# The Electromagnetic Spectrum, Part I

## Lecture 14

**This lecture is an exploration of the nature, the phenomenon, of light.**

James Clerk Maxwell's four equations provided a complete description of electromagnetism and also introduced the concept of the electromagnetic wave. This discovery has had profound consequences, but first let's explore the nature of these waves. Consider a single charged particle—an electron, for example. What happens if the electron moves back and forth, perhaps due to thermal motion?

Every charged particle exerts a force on every other, so a second electron at some distance from the first must sense the varying force. Maxwell discovered that the information from one electron travels to the other electron at 186,000 miles per second—the speed of light. An electron wiggling back and forth is a tiny, varying electric current that must also produce a varying magnetic field. But the varying magnetic field must, in turn, induce a varying electrical field. These radiating electromagnetic fields are light.

To understand more about the nature of light, we need to explore the characteristics of waves. Waves provide an efficient way to move energy without moving mass. Waves can be quantified with four variables, related to their familiar crest-and-trough shape. Wavelength ($\lambda$) is the distance between adjacent crests, while amplitude is the height of the crest. Frequency ($f$) is the number of crests that passes a point per second. Velocity ($v$) is the speed of the crest. Three of these variables are related according to the following formula, which shows that frequency and wavelength are inversely proportional:

$$f = v/\lambda$$

These basic concepts can be applied to electromagnetic waves. First, the only restriction placed by Maxwell's equations on these waves is that they must travel at 186,000 miles per second, or $3 \times 10^8$ meters/second (thus in this formula, $v = c$, or the speed of light). Shorter wavelengths (i.e., higher frequencies) carry more energy per wave.

There is no restriction on wavelength. Curiously, the only form of light known to Maxwell and his contemporaries was visible light, with wavelengths in a very narrow range from about 15 to about 30 millionths of an inch. This situation is analogous to what a person feels in a rowboat on the ocean; only wavelengths close to the boat's length rock the boat. Similarly, humans, with only their eyes as detectors, never suspected the existence of many other wavelengths of electromagnetic radiation. The discovery and subsequent use of these waves in the half century between 1880 and 1930 marks a turning point in science and technology.

**Light is a form of electromagnetic radiation produced whenever an electric charge accelerates.**

The only way for us to know about electromagnetic radiation is for it to interact with matter. There are three types of light-matter interactions.

- Transmission: When electromagnetic waves pass through an object, they are said to be transmitted, and the substance is said to be transparent to those waves.

- Absorption: Electromagnetic waves are a form of energy that may be transferred to matter by absorption. When this happens, the light is often converted to heat energy—a phenomenon you experience when you walk on a black surface on a sunny summer day.

- Scattering: Electromagnetic waves can also bounce off a surface in several distinct ways, including diffuse scattering, reflection, and diffraction.

The conservation of energy demands that the energy of electromagnetic radiation hitting a material must equal the energy of transmitted, absorbed, and scattered radiation.

The electromagnetic spectrum is a continuum of all possible wavelengths. There are no sharp natural divisions of different ranges of light. It is convenient, however, to divide the spectrum into broad types of radiation,

**Marchese Guglielmo Marconi, the father of radio.**

distinguished by how the waves are generated, how they are detected, and how they are used. Common divisions of the electromagnetic spectrum include radio, microwave, infrared, visible, ultraviolet, X-ray, and gamma ray, in order of increasing energy and decreasing wavelength.

Radio waves, the first invisible electromagnetic waves to be discovered, exemplify the behavior of electromagnetic radiation. German physicist Heinrich Rudolf Hertz (1857–1894) discovered the existence of radio waves in a series of experiments in the late 1880s. By 1895, the Italian engineer Guglielmo Marconi (1874–1937) had demonstrated wireless transmission by means of radio waves, and the modern communication era was begun.

- Radio waves include electromagnetic radiation with wavelengths between about a foot and several miles long.

- Radio waves, like all electromagnetic waves, are produced when charged particles move back and forth, or oscillate.

- Radio waves are ideal for communications because they travel through the atmosphere and most building materials.

Information is commonly conveyed on a radio signal in two contrasting ways. All radio broadcasts start with a carrier wave of a set frequency—the number to which you tune your radio. In an amplitude modulation (AM) broadcast, the amplitude of the carrier wave is varied. In a frequency modulation (FM) broadcast, the frequency of the carrier wave is varied. Because radio waves radiate out in so many directions over such great distances, society needs to regulate who can use what wavelengths, or "bands." This is done by international and national organizations (like the FCC). Radio astronomers

use large dish-like antennas to detect radio waves that are emitted from distant objects in space. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 6.

## Supplementary Reading

Sobel, *Light.*

## Questions to Consider

**1.** When Franklin and his contemporaries rubbed amber with fur, they were moving electrical charges in curved paths. Were they producing electromagnetic radiation? If so, what was the approximate wavelength and frequency of that radiation?

**2.** What is so special about visible light that our eyes should detect only this narrow range?

# The Electromagnetic Spectrum, Part II

## Lecture 15

**The electromagnetic spectrum is a continuum, with wavelengths varying from many miles to a fraction of an inch—indeed, the size of an atomic nucleus at the shortest end. This spectrum has no sharp boundaries, but it's conveniently divided into seven broad divisions, and this is based primarily on their distinctive modes of generation and uses—that is, on technological grounds.**

Maxwell discovered that light is a form of electromagnetic radiation—waves of electromagnetic energy that travel 186,000 miles per second. The electromagnetic spectrum is a continuum, with wavelengths varying from larger than stars to smaller than an atom's nucleus, with no sharp boundaries. The spectrum is conveniently divided into broad divisions, based primarily on their distinctive modes of generation and use.

Microwaves include electromagnetic radiation with wavelengths from about a third of a millimeter to a third of a meter—a range that overlaps with the shortest radio waves. They are produced by a rapidly oscillating electric or magnetic field. The microwave oven relies on the fact that water molecules readily absorb microwaves of a frequency of about 2.45 GHz—energy that is converted to heat. This effect was discovered accidentally by Percy Spencer, a physicist who placed his sandwich on top of a microwave generator in his lab. A microwave oven has a microwave generator designed to produce the correct wavelength to heat water. The sides of the oven reflect microwaves, to optimize heating and protect people. A metal object in a microwave oven rapidly absorbs all the microwave energy, causing the object to heat up dangerously. Microwaves can be focused into narrow beams, like a flashlight, and they are not easily scattered by air, so they are often used for secure point-to-point communications.

Radar relies on the reflection of microwaves off solid objects. A radar antenna acts both as the emitter of microwave pulses and as the receiver of reflected microwaves. The direction and time of the microwave echo indicate

the position of an object, while subtle shifts in wavelength reveal the object's speed. Stealth technologies are designed to evade radar by reducing the amount of microwaves reflected back to the source.

Infrared radiation includes electromagnetic waves from about a thousandth to a millionth of a meter. Infrared radiation is emitted by every hot object; we feel this radiation as heat. Skin is a sensitive detector of heat. Infrared imaging technologies play important roles in several fields. Infrared vision goggles and film were first developed by the military to identify targets at night. Similar technologies are now used to evaluate heat loss from buildings. Infrared imaging has been used for the medical diagnosis of breast cancer, faulty circulation, and severe burns. Some earth-observing satellites are equipped with infrared sensors, which have aided in the tracking of forest fires, monitoring of thermal pollution by factories, and prediction of volcanic eruptions.

**Electromagnetic radiation interacts with matter by absorption, transmission, or scattering.**

Visible light, which occurs over the narrow range of about 400–700 billionths of a meter, is defined as the range of wavelengths that our eyes can detect. The spectrum is further divided into smaller divisions called colors. The colors of the visible light spectrum are not equal in width. Our eyes are most sensitive to yellow (570–590 billionth of a meter), which also is the most intense range of light coming from the Sun. Isaac Newton used two prisms to demonstrate that white light results from the combination of all wavelengths of light.

Ultraviolet (UV) radiation, from about 10 to 400 billionths of a meter, has energies that are high enough to damage living tissues. UV radiation is often divided into three ranges.

- The longest UV wavelengths (near UV) are primarily absorbed by the skin. They cause the chemical changes of tanning and production of vitamin D.

- Radiation between about 280 and 320 billionths of a meter (far UV) penetrates more deeply into tissues and can kill cells.

- Radiation with wavelengths between 10 and 280 billionths of a meter (extreme UV) is strongly absorbed by air.

The Sun produces the full range of UV radiation, but only wavelengths longer than about 280 billionths of an inch penetrate to the Earth's surface. The shortest of these UV wavelengths are harmful; prolonged exposure greatly increases the risk of skin cancer. A sun block or sunscreen is a chemical that reflects or absorbs harmful UV radiation before it can reach the skin. A novel use of UV radiation is in "black light" shows.

X-rays are the highest-energy radiation that can be produced by routine electronic technologies. These ionizing waves range from about 0.1 to 100 billionths of an inch. X-rays were discovered in 1895 by Wilhelm Conrad Roentgen (1845–1923), who was using a high-energy electron tube and noticed that a nearby chemical began to fluoresce. The great penetrating power of these rays, combined with the fact that they were absorbed by some kinds of photographic plates, made them ideal for seeing the hidden structures of the body. They quickly found use in medical diagnosis. A dental X-ray illustrates how this process works. X-rays diffract off planes of atoms in crystals. The direction and intensity of this diffraction reveals the arrangement of atoms in a crystal.

Gamma rays are the highest-energy electromagnetic waves in nature, with wavelengths shorter than 100 trillionths of a meter. Gamma rays are produced in nuclear reactions and in processes associated with stars in deep space. Government laboratories produce small quantities of gamma ray–emitting chemicals for use in medicine and research. Gamma rays are used in special cases for medical diagnosis. Minor amounts of these chemicals can also be used as environmental tracers, to monitor air and water. Physicists use gamma rays to probe the structure of the atom. The Gamma Ray Observatory, a satellite telescope launched in 1991, has revealed surprising, and as yet not fully explained, bursts of gamma rays coming from distant parts of the universe.

In general, the shorter-wavelength, higher-energy portions of the electromagnetic spectrum—ultraviolet, X-ray, and gamma ray—are the most dangerous to life. But controversy has recently swirled about extremely low frequency (ELF) radiation. Waves at frequencies of tens to thousands of cycles per second have no technological applications but are constantly produced in our environment by the pervasive power grid and all appliances that feed off of it. ELF radiation at frequencies of 15,000–30,000 cycles per second is produced by video display terminals.

Most people's exposure—even for people living close to a power line—is similar to the norm, because the field strength drops off very quickly with distance from power lines or appliances. High levels of exposure are usually associated with specific jobs, including power line workers and electric arc welders. Anecdotal evidence of increased cancer in the vicinity of high-power lines has led to several large-scale studies of the possible human health hazards of ELF radiation. So far, there is no convincing evidence of increased health risks. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 6.

## Supplementary Reading

Sobel, *Light*.

## Questions to Consider

1. What constitutes an "acceptable" risk for exposure to electromagnetic radiation at home, in the workplace, and at the doctor's office? How should the government regulate such exposures?

2. As humans evolved, they had to survive at night as well as during the day. Why didn't humans evolve night vision?

# Relativity

## Lecture 16

**The theory of relativity: Perhaps no other idea in science evokes the sense of strangeness and abstraction of modern physics. Perhaps no other idea has been more misunderstood or more misrepresented. But at its root, relativity is a relatively simple concept. Its great underlying principle is that the laws of nature are independent of the observer's frame of reference.**

Maxwell's equations claim that the speed of light is a universal constant, 186,000 miles per second, for every observer in the universe. But this statement leads to a stunning paradox. In our everyday experience, velocities are additive. Different observers describe the same events differently in different "frames of reference." A classic example occurs when you flip a coin in a moving car. There is no one "correct" frame of reference. Think about the behavior of light. You will measure the speed of light coming from a flashlight to be 186,000 miles per second, no matter how fast the flashlight is moving.

Albert Einstein thought about this situation and realized that there are three ways to resolve the dilemma. Perhaps the laws of nature are different in different frames of reference, so that different versions of Maxwell's equations are required in different situations. Einstein rejected this idea. Maxwell's equations could be wrong, but Einstein was also reluctant to make that conclusion, because Maxwell's electromagnetism was so complete and thoroughly tested. Our common sense about the way velocities add could be wrong, since our everyday experience does not deal with objects traveling anywhere near 186,000 miles per second.

The principle of relativity states that the laws of nature are the same in every possible reference frame. Einstein's theory of relativity considers the consequences of light having the same speed in all reference frames. The first part of Einstein's theory, called special relativity (published in 1905), deals only with reference frames in uniform motion. The second part, called

general relativity (published in 1916), deals with accelerating reference frames and is mathematically much more complex.

Einstein began thinking about relativity while looking out a trolley car window moving away from a clock tower, just as the clock was about to strike noon. He imagined what he would see if the trolley car sped up, faster and faster, close to light speed. He realized that he would be "surfing" on the light waves that carried the information that it was noon. The pocket watch he carried with him would tick away seconds. The clock tower, however, would appear to slow down and stop. The astonishing conclusion is that the measurement of time, just like the measurement of motion, is relative to the observer's frame of reference.

The idea that time is relative to the observer can be demonstrated by the analysis of a light clock. A light clock incorporates a light that flashes on and off, a light sensor, and a mirror. When the light flashes, the light pulse travels to the mirror and bounces back to the sensor, which triggers another flash. Each flash is like the tick of a clock. The length of the tick depends only on the distance the light travels. If the clock is stationary with respect to you, then it will tick every time the light travels the distance from the light to the mirror and back. If the clock is moving with respect to you, then the light has to travel farther than twice the distance, and it will appear to tick more slowly.

Calculating the exact amount of this "time dilation" is a straightforward problem in plane geometry. Every time your watch ticks one second, the light clock moving at velocity $v$, only ticks a fraction of a second $t$:

$$t = \sqrt{1 - \left(\frac{v}{c}\right)^2}$$

The fraction on the right is called the Lorentz factor, and it appears often in relativistic calculations. This number is always between 1 and 0. When velocity is 0, the Lorentz factor is 1, and clocks behave normally. A table of velocity–versus–Lorentz factor gives a sense of this effect:

**Velocity versus Lorentz Factor**

| *v* (mi/sec) | Lorentz factor |
|---|---|
| 0 | 1 |
| 1 | 0.99999999997 |
| 10 | 0.999999997 |
| 100 | 0.9999997 |
| 1,000 | 0.99997 |
| 10,000 | 0.997 |
| 100,000 | 0.711 |
| 150,000 | 0.350 |
| 180,000 | 0.063 |
| 186,000 | 0 |

This table suggests that relativistic effects are barely noticeable at velocities below about 10,000 miles per second (relative to the observer). If the relative velocity of an object ever reached 186,000 miles per second, or *c*, then the Lorentz factor is 0 and time appears to stop for that object. Time dilation is of little concern today, but in a future of high-speed space travel, time dilation could cause havoc with our lives. Relativistic space travelers age at only a fraction of Earth-bound relatives.

Special relativity has other strange and unexpected consequences. Moving yardsticks appear shorter than stationary ones. The fractional shortening is equal to the Lorentz factor. If an object could be accelerated to the speed of light, its length would shorten to zero. This effect is observed in particle accelerators.

Mass also depends on velocity; the greater the relative velocity, the greater the mass of an object. The increase in mass is inversely proportional to the Lorentz factor. Mass is defined as an object's resistance to being accelerated by a force. As an object approaches light speed, its mass appears to approach infinity. It would require an infinite force to accelerate an object to the speed

of light. For this reason, special relativity forbids any object with mass to travel at the speed of light.

If light speed is constant in all reference frames, then time, length, and mass must be relative. A few months after formulating these remarkable ideas, Einstein realized another profound implication of special relativity: The first law of thermodynamics must apply to every reference frame—the total amount of energy must be constant. But since mass increases with velocity, the total amount of kinetic energy can't follow the energy conservation law. Einstein published a short, revolutionary note explaining this seeming paradox—mass itself was missing from the energy balance sheet. Mass has a rest energy equal to its rest mass times the speed of light squared: $E = mc^2$.

General relativity, which deals with frames of reference that accelerate, provides a new perspective on the nature of forces. Consider another thought experiment: If you were in a sealed room on a spaceship accelerating at exactly 1 *g* (the gravitational acceleration at the Earth's surface), is there any way that you could tell the difference between the spaceship and Earth? The answer, Einstein concluded, is no.

Gravitational forces and acceleration are equivalent, and the distinction between one and the other is arbitrary, based on our frame of reference. Newton thought of a universe as a flat surface: Balls roll in a straight line and at constant velocity unless acted on by a force. Newton would say that the Moon orbits the Earth because of a gravitational force. Einstein saw the universe as a warped surface. Balls follow contours along this curved surface.

The ultimate test of any theory is whether or not it makes successful predictions. While it is not easy to detect most relativistic effects, there are a few specific ways in which the predictions of Newton and Einstein differ. According to Einstein, light should follow the warping of space and thus bend. The gravitational bending of light by massive objects in space is now well documented. The exact shapes of orbits differ slightly in the Newtonian and Einsteinian formulations; meticulous observations show that Einstein's model works. Einstein predicts that the frequency of a light shining upward in a gravitational field should decrease slightly, while light shining down

in the field should increase in frequency. These predictions have also been demonstrated. These observations do not mean that Newton was wrong, nor that his laws of motion should be abandoned. These laws work perfectly at everyday velocities. Einstein's formulation is just more inclusive, for it treats motion at both low and high velocity. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 13.

## Supplementary Reading

Lightman, *Einstein's Dreams*.

Pais, *Subtle Is the Lord: The Science and Life of Albert Einstein*.

Wolfson, *Einstein's Relativity and the Quantum Revolution: Modern Physics for the Non-Scientist*.

## Questions to Consider

1. The central assumption of relativity is that the laws of the universe are the same everywhere. Can this assumption be tested? Is it reasonable?

2. How might relativistic space travel affect genealogical methods? How might family trees be affected?

# Atoms

## Lecture 17

**I want to tell you about one of the most profound discoveries of science, and that is that atoms are submicroscopic particles from which all objects are made.**

Since ancient times, philosophers have asked, "Of what is the physical world made?" Does every different material possess its own unique essence, or is there a more fundamental kind of substance? Until relatively recently, this question was beyond the methods of science. Nevertheless, logic suggested that there are two possible answers: Substances might be a continuum, infinitely divisible, always possessing the properties of the bulk, or substances might be made up of smaller particles, which do not possess the properties of the bulk.

The Greek philosopher Democritus (c.460–370 B.C.) developed a philosophical rationalization for the existence of atoms. Atoms represent a solution to the dilemma of "the one and the many." Philosophers were convinced that the essence of nature is elegant and simple, reflecting a universal unity. But the real world is complex and messy. Atoms allowed for external complexity with internal unity. He summarized his ideas in a famous quotation: "In reality, there are only atoms and the void." The four elements—earth, air, fire, and water—were another, similar attempt.

Aristotle ultimately rejected atomism because no atomic properties could be perceived by the senses. Lucretius (94–55 B.C.) was one of the few ancient scholars who dared to dispute Aristotle's opinion. His work *De Rerum Natura* propounds an atomic theory. He argued that infinitely divisible matter led to unacceptable problems in distinguishing matter from nothingness. Unfortunately for the idea of atomism, some of Lucretius's other writings suggested a leaning towards atheism—a stand that tended to discredit all his work for many centuries.

No matter how persuasively argued, these philosophical speculations on the nature of matter and the existence of atoms were just that—speculations. The

Swiss physicist Daniel Bernoulli (1700–1782) realized that if atoms are real, they must have mass and velocity, and thus kinetic energy. He successfully applied Newton's second law of motion to atoms to explain the behavior of gases under pressure. Doubling the number of gas particles, or halving the volume, doubles the number of collisions between the gas and the confining walls. This increase also doubles the pressure. Increasing temperature increases the average velocity of the gas particles, also increasing pressure.

English meteorologist John Dalton (1766–1844) presented the first statement of the atomic theory from a chemist's point of view in his three-volume treatise *A New System of Chemical Philosophy* (1808–1827). Dalton was a poor country teacher who gradually became known for his meteorological observations. One of his noted papers stemmed from an embarrassing incident when he inadvertently learned of his own red-green color blindness. His research led to the first scientific publication on the phenomenon of the common variety of color blindness called daltonism. Dalton's atomic theory states that matter is composed of atoms of perhaps several dozen varieties—the different elements. These elements differ in their weights and sizes. Simple ratios of elements in chemical compounds suggested to Dalton the reality of atoms, but many contemporaries still saw atoms as merely a convenient fiction.

The discovery in 1896 of radioactivity, by which individual atoms emit radiation, provided a compelling piece of evidence for the atomic theory. Certain phosphors flash when hit by this radiation—a process called scintillation.

An atomic effect visible in the microscope is Brownian motion—an erratic, jiggling motion observed in tiny dust particles of pollen grains suspended in water. In 1905, Albert Einstein (1879–1955) demonstrated mathematically that such motions must result from a force—the force of random collisions of atoms.

If atoms are real, then there must be a large but finite number of them in a given quantity of material. Physicists and chemists tried many different ways to determine this number; if atoms are real, all approaches should lead to the same number. By early in the 20$^{th}$ century, estimates from

studies of radioactivity, Brownian motion, and other methods all converged on the same number—about $6 \times 10^{23}$ atoms per mole. This is known as Avogadro's number.

X-ray crystallography, developed in 1912, convinced any remaining skeptics by demonstrating the sizes and regular arrangements of atoms in crystals. X-rays diffract off of crystals because the size of atoms is similar to X-ray wavelengths. In 1980, the first photograph of an individual atom was taken at the University of Heidelberg in Germany. Now, studies of individual atoms are undertaken around the world.

**Atoms are submicroscopic particles from which all objects are made.**

Dalton visualized atoms as tiny hard spheres. Yet, even as scientists were confirming the atomic theory, they discovered another layer of complexity: Atoms are made of still smaller particles. Studies of electricity suggested that there had to be some kind of substance—Franklin's electrical fluid—that could be stripped off atoms.

British physicist Sir Joseph John Thomson (1856–1940), universally known as J. J., spent much of his research career studying phenomena associated with electromagnetism. If a spark-producing device is sealed in a vacuum, then the charge flows much more steadily, without sparks. This flow of electricity is the principle behind the vacuum tube—which dominated all electronics before about 1960. Thomson discovered that a magnet deflects the invisible current, and he concluded that the beam has electric charge and mass. He used Newton's laws and Maxwell's equations to determine the nature of the electric fluid, which he called electrons. Electrons have a mass less than a thousandth of the mass of the atom. It was clear to Thomson that when electrons are stripped off an atom, the atom has a positive residual charge.

The fragmentation of atoms by radioactivity led to the discovery of the atom's surprising structure. This work was undertaken by Lord Ernest Rutherford, a protege of Thomson, who established his own physics lab at the University of Manchester. In 1909, Rutherford's group began to use radioactivity to study

the structure of the atom. Radium emits alpha particles, which behave like tiny bullets. A beam of these particles was aimed at a gold foil. Almost all of the alpha particles passed right through the gold, to be recorded as a flash on a fluorescent screen. But about 1 in 1000 alpha particles was scattered backwards at a high angle. Rutherford concluded that the atom is almost entirely empty space, with a tiny, hard nucleus that carries a positive charge and almost all of the atom's mass. Around this nucleus orbit negatively charged electrons. But great mysteries still remained: What holds the atom together? And how do atoms interact with light? ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 7.

## Supplementary Reading

Andrade, *Rutherford and the Nature of the Atom*.

Harre, *Great Scientific Experiments*, Chapters 10 and 16.

Perrin, *The Atom*.

Thomson, *J. J. Thomson, Discoverer of the Electron*.

von Baeyer, *Taming the Atom*.

## Questions to Consider

1. Since atoms are much too small to detect in any straightforward way, does it make any difference whether they are real or not?

2. What physical evidence would convince you that atoms are real?

# The Bohr Atom

## Lecture 18

**To understand the behavior of atoms, we have to introduce a remarkable and a counterintuitive model called the Bohr atom, and we have to introduce the great principle that electrons and atoms adopt stable orbits at specific energies. In this lecture … I focus on the curious behavior of electrons, electrons in orbit around the nucleus of an atom.**

Experimental proof of the atomic theory was one of the great triumphs of 20th-century science. The convergence of many lines of evidence—the chemists' law of combinations, the physicists' studies of radioactivity and Brownian motion, the discoveries of X-ray crystallography—left little doubt that atoms are much more than a useful fiction. Ernest Rutherford's concept of the atom, with swift, light, negatively charged electrons circling around a tiny, massive, positively charged nucleus was simple, elegant—and impossible. Just as an Earth-bound satellite must eventually spiral in and crash into the Earth, so must Rutherford's electron satellites eventually collide with the nucleus.

**Electrons in atoms adopt stable orbits at specific energies.**

A possible solution to this dilemma was proposed by the Danish physicist Niels Bohr (1885–1962). In 1913, he developed an atomic model that is strange and counterintuitive. Bohr developed his model after studying the way glowing hydrogen gas gives off light. Rather than a continuous spectrum of light, as one sees in a glowing light bulb, hot hydrogen gives off light only at a few, specific wavelengths. The specific wavelengths observed for hydrogen, Bohr suggested, imply that electrons must adopt specific energies and jump from one energy to another.

In the Bohr atom, electrons can reside in several discrete stationary states at well-defined distances from the nucleus. An electron can remain in such a state without accelerating. Light is emitted only when an electron jumps from one orbit to another at lower energy. The lowest-energy orbit of an

electron is called the ground state; all higher energy states are called excited states. As electrons hop from state to state, light is produced.

The Bohr atom lies outside the realm of our everyday experience. Nevertheless, comparisons with several more familiar systems may help in understanding the strange world of the atom. The energy levels of electrons are something like steps of a long staircase. You can place an object stably on one step or another, but not in between two steps. Different orbits have different electromagnetic potential energy, just as different steps have different gravitational potential energy. The Bohr atom is not like a miniature solar system. In the solar system, a planet can be at any distance from the Sun, but electrons in a Bohr atom must lie at specific distances. The Bohr atom was embraced by physicists because it was extremely successful in modeling the behavior of atoms and their interaction with light.

The Bohr model of the atom helped to explain many of the properties of light-matter interactions. The model postulates that energy and light must come in discrete packets, called quanta. The smallest possible increment in energy is represented by an electron's jump from one orbit to the next—a quantum jump. A quantum jump from a higher to a lower energy orbit releases one quantum of electromagnetic radiation, called a photon. When an atom absorbs a photon, an electron jumps to higher-energy orbit.

Fluorescence, by which a material subjected to ultraviolet light glows brightly in visible wavelengths, is easily explained by the Bohr model. Day-Glo colors are examples of this phenomenon. Mercury vapor street lights, with their distinctive bluish-white glow, and bright yellow sodium vapor lamps are other examples of quantum leaps in everyday life.

Spectroscopy is the study of these light-matter interactions. A spectrum, or spectrograph, is a graphical record of light intensity over a range of wavelengths—typically a small subset of the entire electromagnetic spectrum. Different wavelengths appear along the *x* axis of the graph. The *y* axis of the graph indicates the intensity of different wavelengths of light. Spectra are measured with a spectroscope, which records light intensity as it separates white light into different wavelengths.

Several different kinds of spectra are important in research. One of the first applications of spectroscopy was the study of flame spectra. A glowing object produces an emission spectrum. Each element has a distinctive spectrum; several new elements were discovered in this way. Studies of stars and other astronomical objects would be impossible without spectroscopy, which enables scientists to study emission spectra. The element helium was first observed in the spectrum of the Sun.

If light passes through a transparent material such as a gemstone, glass, or air, the result is an absorption spectrum. Absorption spectra reveal pollutants in the atmosphere and so are critical to environmental monitoring. All valuable gemstones are certified by spectroscopic techniques, which can readily distinguish natural from artificial gems.

Spectra can also be obtained by reflecting light off an object's surface. Reflectance spectra are critical in astronomy, because they reveal compositional information about remote objects. Composition maps of the Moon and Mars have been obtained from orbiting satellites equipped with reflectance spectrometers.

Spectra of common objects reveal that our eyes and brain perceive and interpret many different kinds of emission, absorption, and reflection phenomena as colors. Eyes have three different kinds of color receptors, or cones, that are sensitive to blue, green, and red light. We perceive white light as the presence of equal intensities of blue, green, and red light. Partial color blindness results from defects in any of the three types of color receptors.

The laser makes special use of the quantum interactions between light and matter. "Laser" is an acronym for "light amplification by stimulated emission of radiation." The principal components of a laser are a collection of atoms that have one dominant quantum jump, a source of energy to stimulate those atoms to an excited state, and a pair of parallel mirrors to align the resultant light. The collection of atoms may be a gas, a liquid, or a crystal. Electrical energy supplied to the laser is used to "pump" the atoms into their excited state. The two mirrors align a beam of photons. One of the mirrors is partially transparent and lets a small fraction of the light out as a pencil-thin laser beam.

Laser light differs from light from an ordinary flashlight in three important ways. While flashlights emit white light, laser light is monochromatic—of a single wavelength. Flashlights emit a cone of light that disperses with distance. Laser light forms such a tight, directional beam that a laser shown from Earth will bounce off the Moon. Flashlights emit light waves in which the crests and troughs of the waves don't line up. Laser light is "coherent," with all the waves exactly in synch. The special qualities of laser light have hundreds of applications in science, industry, and medicine. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 7.

## Supplementary Reading

Harre, *Great Scientific Experiments*, Chapter 15.

## Questions to Consider

1. Identify a device in your home that can be used to determine a spectrum for waves in the KHz and GHz range of frequency.

2. Explain the statement that human eyes are a biological spectrometer.

# The Quantum World

## Lecture 19

**The Bohr atom, and its astonishing success at describing the interaction of light and matter, provides a wonderful starting point for our consideration of chemistry and chemical elements.**

The study of motions at the scale of quantum jumps is called quantum mechanics. In this lecture, we will explore this strange physical world that operates at the atomic and subatomic scales. Before entering this atomic realm, it is best to leave behind preconceptions about how the world should behave. No one has experienced nature at the atomic scale so our intuition may not be of much use.

The first nonintuitive fact regarding atomic-scale processes is that every measurable quantity comes in discrete bundles, called quanta. The idea of quanta was first proposed by the German physicist Max Planck (1858–1947) in 1900 to explain the spectrum of electromagnetic radiation emitted by a black body. An ideal black body absorbs all electromagnetic radiation that falls on it. The laws of thermodynamics require that this energy be re-radiated into the surroundings; the spectrum of this radiated energy is what concerned physicists in the late 19th century.

Classical theory, which deals with energy as a continuum of wavelengths, overestimates the amount of energy that would be radiated at very short wavelengths. To solve this problem, Planck suggested that energy comes in discontinuous steps, or quanta. The energy ($E$) carried by an electromagnetic wave, is given by the wave's frequency times a constant, now known as Planck's constant: $E = hv$, where the constant $h = 6.63 \times 10^{-34}$ joule · sec. With this formulation, Planck was able to match the observed black-body behavior. Few physicists were ready to accept this strange and abstract idea at that time.

In 1905, Albert Einstein reinforced Planck's theory in studies of the photoelectric effect, by which light can eject electrons from certain metals. A puzzling aspect of the photoelectric effect is that velocities of ejected

photoelectrons are independent of the light's intensity, whereas velocities increase with shorter wavelengths (higher frequencies). Einstein adopted Planck's postulate, that light waves carry energy $hv$, and he showed that the kinetic energy of the electrons matched the Planck energy of the light.

The Bohr atom, introduced in 1913, elaborated on the idea of quantized atoms. Many atomic-scale properties are quantized. Mass is quantized; you cannot have half an electron. Energy is quantized into the discrete energy levels of electrons in atoms, and electromagnetic radiation comes in the individual units called photons. Electric charge comes in integral increments. Under most circumstances these quantum effects don't affect the macroscopic world in any obvious way.

The quantization of the atomic world implies that every measurement must change the object being measured. Every measurement requires three things: a sample, a source of energy, and a detector. The sample is a piece of matter. The source of energy—light, heat, or kinetic energy, for example—must interact with the sample. A detector measures the interaction of sample and energy.

Examples to illustrate the quantization concept:

- When you look through a microscope, a source of light energy illuminates the sample, and you observe with your eye.

- When police set up a speed trap, your car is the sample, their microwaves (radar) are the energy, and their microwave receiver is the detector.

Giant accelerators used by particle physicists are elaborate devices to subject a sample (a beam of subatomic particles) to energy (the kinetic energy of other particles) and to detect the interaction. At the scale of the atom, the smallest increment of energy is the photon, which, if it interacts with the atom, must change the state of the atom. This situation is analogous to trying to find the location of a bowling ball in a darkened room by rolling other bowling balls into the room and listening for a clunk.

German physicist Werner Heisenberg (1901–1976) expressed the dilemma of quantum-scale measurements in an elegant mathematical form, known as the Heisenberg uncertainty principle. He said that you can't know the exact position and velocity of an object at the same time. You can know either the position or the velocity to any arbitrary precision, but the more you constrain down one, the more uncertain is the other. The uncertainty principle means that we must use probabilities, not certainties, to describe any specific quantum-scale event. Given the huge numbers of electrons that we normally have to deal with, probabilities work exceptionally well in describing the quantum behavior of electrons in electronics and other systems.

**Energy, mass, and other properties at the subatomic scale are quantized; at that scale, it is impossible to measure the state of a particle without changing the particle in the process.**

When solving probability functions for electrons, physicists quickly saw that mathematical solutions could take the form of either a particle-like or a wave-like object. Which does an electron look like? One way to differentiate between particles and waves is to see how they behave when you direct them at a parallel pair of narrow slits. When solid particles like ping-pong balls are directed at a pair of slits, they go through the first, or go through the second, or bounce back. The result is two separate piles of balls. When waves of sound or water are directed at two slits, they create a pattern of interference, with many maxima and minima on the far side of the slits.

This experiment has been tried many times with electrons. When single electrons are fired at the slits, they produce single spots on a photographic film, suggesting that electrons are isolated particles. When thousands of electrons are fired at a pair of slits, the thousands of separate spots reveal a clear wave-like interference pattern. The conclusion is that electrons behave both as particles and as waves (wave-particle duality).

Wave-particle duality brings us full circle to the Bohr atom and its strange non-accelerating electron orbits at discrete energy levels. Consider stable

electron orbits for a hydrogen atom with one electron and one proton in the nucleus. If the electron is thought of as a particle, then Newton's equations of motion can be used to analyze its possible orbits, just like the possible orbits of a moon or planet. If a planet is to achieve a stable circular orbit, then the gravitational force pulling down on the planet must be exactly balanced by the planet's orbital velocity. Similarly, if an electron is to achieve a stable orbit, then the attractive electrostatic force between the electron's single negative electric charge and the nucleus' single positive electric charge must be exactly balanced by the orbital velocity of the electron.

If the electron is thought of as a wave, then there must be a form of wave that can adopt a circular orbit. Waves, in general, can occur in any wavelength. When a wave is restricted to lie in a circle, however, then it must take the form of a standing wave with an integral number of wave crests. This feature can be illustrated by any vibrating string. If an electron is to achieve a stable standing wave orbit, then an integral number of wave crests must fit into that orbit. Electron orbits of hydrogen atoms correspond to the solutions of two completely different equations—one for particle behavior and one for wave behavior. Bohr orbits correspond to all the possible solutions for orbits that satisfy the equations for electrons both as particles and as waves.

The quantum world is strange and different from anything we experience in the world of baseballs and automobiles. The strength of science is that it constrains us to describe the world as it is, not as we wish it to be. If everyday metaphors fail in the description of the quantum world then, perhaps, science can enrich our lives with new metaphors. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 8.

## Supplementary Reading

Cassidy, *The Life and Times of Werner Heisenberg*.

Wolfson, *Einstein's Relativity and the Quantum Revolution: Modern Physics for the Non-Scientist*.

## Questions to Consider

1. What is the role of metaphor in science? Is an equation that describes a natural law a metaphor?

2. Some scholars following Newton feared that the laws of motion preclude the possibility of free will. How might quantum mechanics relate to this issue?

# The Periodic Table of the Elements

## Lecture 20

**The periodic table is the chemist's playground, this icon of science that's found on science classroom walls by the millions all over the country, all around the world. It's one of the most powerful conceptual tools in all of science, yet it didn't spring forth all at once.**

All of the chemical elements are systematized in the periodic table of the elements, the chemist's playground. This icon of science, found in copies by the million in classrooms around the world, is one of the most powerful conceptual tools in science, yet it did not spring forth fully formed. This table represents countless centuries of collective work—work that continues today.

Long before the existence of atoms was proven, chemical researchers realized that certain substances seemed to be more fundamental than others. These elements could not be broken down into other substances by any ordinary physical or chemical means. The identification of the chemical elements has a long history. Ancient cultures knew of at least ten elements, most of which were found in their native state in nature. The precious metals copper, silver, gold, and platinum were common enough to be noticed, hard enough to be useful, and rare enough to be valued. The metals iron, tin, antimony, mercury, and lead were easily produced in a fire from common ores by simple smelting techniques. And the nonmetals carbon (from charcoal) and sulfur (from volcanoes) were also well known in prehistoric times. Alchemists of the 12$^{th}$ through 16$^{th}$ centuries learned to separate a few other elements by fire—arsenic, zinc, bismuth, and phosphorus.

Between 1735 and 1805, chemists devised new techniques to purify and characterize more than two dozen new elements. The battery provided an important new technique, called electrolysis, by which new elements could be isolated.

The Russian chemist Dmitri Mendeleev (1834–1907) knew of 63 chemical elements when he began working on his famous table in the 1860s. Chemical

elements have a number of measurable properties, which provide the basis for grouping the elements in various ways. The relative weights of elements were determined by observing the ratios of their weights when compounds are decomposed. Elements also displayed systematic properties during electrolysis. A few elements, including oxygen, chlorine, and bromine, always appeared at the positive electrode. These gases could be collected as they bubbled up through the solution. Metals were deposited on the negative electrode. This is the principle behind electroplating.

**All of the chemical elements are systematized in the periodic table of the elements.**

Long before Mendeleev's work, chemists recognized that some groups of elements show striking similarities in their physical appearance and chemical reactivity. The elements lithium, sodium, potassium, and rubidium, for example, are all soft, silvery metals, called the alkali metals. The elements beryllium, magnesium, calcium, and barium, known collectively as alkaline earth metals, form 1:2 compounds with chlorine (such as $CaCl_2$) and 1:1 compounds with oxygen (such as CaO, or lime). Chlorine, bromine, and iodine are all highly reactive nonmetals that form 1:1 compounds with hydrogen and alkali metals and 2:1 compounds with alkaline earth metals. Part of Mendeleev's success in developing the periodic table was his ability to focus on the most obvious patterns and not worry too much about anomalies.

Scientists readily accepted the concept of the periodic table not only because it systematized so much known data about the elements, but also because it made specific, testable predictions about elements that had not yet been isolated.

New elements continued to expand the periodic table. The development of flame spectroscopy triggered a wave of element discoveries in the mid-1870s through the 1890s. More than two dozen rare elements (e.g., the rare earth elements, atomic numbers 57–71, and the inert, or noble, gases) were identified with this new technology. The isolation of fluorine remained a great challenge of the late $19^{th}$ century. In 1886, French chemist Henri Moissan successfully succeeded after almost three years of effort. Polish

chemist Marie Curie, assisted by her husband Pierre, isolated the first of the radioactive elements, polonium and radium, in 1898. These elements spontaneously emit high-energy radiation and transform into other elements, as we shall see in Lecture 27.

Development of the Bohr atomic model led to a deeper understanding of why the periodic table works. The periodic table systematizes two key properties of the elements: their weight and their chemical properties. The weight (or mass) of elements increases from left-to-right and top-to-bottom of the periodic table. Rutherford showed that almost all of the mass of an atom is in its positively charged nucleus. Increasing weight corresponds to increasing size of the nucleus and, therefore, increasing positive charge. An element's atomic number represents both its position in the periodic table and the number of protons in the nucleus. For an atom to be electrically neutral, it must have the same number of electrons in orbit as protons in the nucleus. Any difference in the number of protons and electrons results in an electrically charged atom, or ion.

The chemical behavior of an element is a reflection of the interaction between the electrons of two or more atoms. The periodic properties of the elements suggest that elements with similar chemical properties have similar arrangements of outer electrons. These elements are arranged in columns.

We now know that electrons combine in shells around the nucleus. Each row of the periodic table corresponds to one of these electron shells. Moving from left to right along a row of the table corresponds to adding positive charges to the nucleus. For the atom to be electrically neutral, electrons must be added to the outer shell.

The key to understanding how atoms combine is that certain magic numbers of electrons are much more stable than other numbers. The most stable electron arrangements contain exactly 2, 10, 18, 36, 54, or 86 electrons. Much of chemistry can be understood as a game in which every atom or group of atoms adopts a strategy to achieve one of these magic numbers of electrons. These strategies are called chemical bonding, which is the subject of the next lecture. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 7.

## Supplementary Reading

Emsley, *The Elements*.

Levy, *The Periodic Table*.

van Spronsen, *The Periodic System of Chemical Elements: A History of the First Hundred Years*.

## Questions to Consider

1. What does the history of discovery of chemical elements imply about the role of technology in science?

2. In what ways is the periodic table more useful than, for example, an alphabetical list of all the elements and their properties?

# Introduction to Chemistry

## Lecture 21

**[This] introduces this rich subject of chemistry by focusing on the most basic principle of chemistry: that atoms combine by rearranging their electrons.**

Atoms typically bond to other atoms to form the materials of the physical world. This behavior is a consequence of the extreme stability of arrangements with 2, 10, 18, 36, 54, or 86 electrons. The key to understanding why atoms bond is energy: all natural systems tend to adopt a state of lowest energy.

Imagine a steep-walled valley with boulders strewn about. The most stable place for the boulders is on the valley floor; once there, it takes energy to roll a boulder to a higher level. Boulders could come to rest in depressions or ledges on the sides of the valley, but they would have more gravitational potential energy. A slight earthquake could jostle these boulders loose, sending them to the valley below; their potential energy would end up as heat.

**Electrons rearrange to form chemical bonds.**

The arrangements of an atom's electrons are analogous to the position of boulders in a valley. An arrangement with the outer electron shell completely filled has the lowest chemical potential energy, like a boulder on the valley floor (cf., the inert gases). An arrangement with an unfilled outer shell has higher chemical potential energy. A change to a new arrangement with filled electron shells may be accompanied by a release of energy (cf., the halogens such as chlorine). Different numbers of electrons correspond to different heights on the sides of the valley. If certain arrangements of electrons were not especially stable, then there would be no reason for atoms to bond together. Instability leads to bonding.

Atoms adopt three strategies that allow them to link together: ionic bonding, metallic bonding, and covalent bonding.

In ionic bonding, atoms or molecules with magic numbers of electrons are particularly stable. Atoms that differ from the magic numbers by just one or two electrons are particularly unstable. Chlorine (element 17), for example, is extremely dangerous because each atom will steal an electron from almost any other element to achieve a 10-electron state. Similarly, sodium atoms (element 11) react violently with air or water in order to lose one electron. Ionic bonding, which forms tough hard materials like rocks, glass, and ceramics, combines these two processes. When a chlorine atom approaches a sodium atom, the chlorine atom takes an electron from the sodium atom. The reaction is violent and swift, with a hot flame that indicates a release of energy. Both atoms end up with 10 electrons. In the process, both atoms become electrically charged ions. Chlorine becomes a −1 negatively charged ion, while sodium becomes a +1 positively charged ion. Positive and negative charges attract each other, so the atoms form a chemical bond, called an ionic bond.

Numerous examples of ionic bonding occur around us. All of the elements in the first column of the periodic table (the alkali metals) bond ionically to all the elements in the next to last column of the periodic table (the halogens) to form 1:1 compounds, called alkali halides, or salts (e.g., potassium iodide, the source of iodine in common table salt, sodium chloride). Elements of the second column, including magnesium, calcium, and barium, also form salts with halides. In this case, however, the second-column elements want to give away two electrons, so a 1:2 formula results. An important example is flourite (CaFl), the common mineral containing the element flourine.

One of the most common types of ionic bonding in nature links silicon (element 14) and oxygen (element 8). Strong Si-O bonds are found in $SiO_2$, the common mineral quartz that makes most beach sand, as well as most other rock-forming minerals, window glass, china, and other ceramics. Recall from Coulomb's Law (Lecture 11) that the electrostatic force between two charged particles is proportional to the charges. Another metal, the compound corundum ($Al_2O_3$) is extremely strong and is used in abrasives. It is also the mineral in rubies and sapphires, very hard gems.

The distinctive character of ionic bonds leads to distinctive properties. Ionic bonds feature strong forces in specific directions, between positive

and negative ions; ionically bonded materials like china, glass, and rocks are tough, but brittle. Light waves scatter most easily off of electrons; in many ionic compounds, all the electrons are locked into filled shells, so light passes through relatively easily. Also, because electrons are so tightly held, ionic compounds make excellent electrical insulators.

The second type of chemical bonding is metallic bonding, in which atoms adopt the strategy of sharing electrons. In sodium metal, each atom releases an electron, creating a sea of negatively charged, unbound electrons. The resulting sodium ions are like positively charged islands in that electron sea.

More than three-quarters of the elements in the periodic table form metallic bonds. All elements with an outer shell less than half full form metallic bonds. Most combinations of metallic elements, called alloys, also form metallic bonds. The most common alloys are brass (copper + zinc), bronze (copper + tin), and pewter (tin + antimony). Modern steels are alloys of iron and carbon and often several other elements to give specific properties. The use of aluminum and titanium in making lightweight, very strong alloys used for spacecraft, aircraft, trains, and other transportation applications is evident from Newton's Second Law, $F = ma$ or $a = F/m$. By lowering the mass, greater acceleration can be achieved with less force.

Metallic bonds have a number of distinctive properties. Bonds formed between positive atoms and the sea of negative electrons are not particularly directional. Thus, most metals can be bent without breaking. The mobile electrons of metals reflect light, so they have a shiny surface. Metals make excellent electrical conductors because electrons are free to move.

The third type of chemical bonding, covalent bonding, relies on electron sharing of a different kind. When two hydrogen atoms come together, each atom begins with one electron and one proton, but each atom would rather have a filled shell with two electrons. The two hydrogens form an $H_2$ molecule (a gas) and share the electrons. The link between the two atoms is a covalent bond. This bond contrasts with a hypothetical H-H ionic bond between a +1 and a −1 ion. This bond also contrasts with a hypothetical hydrogen metal, in which many protons are surrounded by a sea of shared electrons.

Covalent bonds occur in many of the nonmetallic objects. The most abundant gas molecules of the atmosphere, $O_2$ and $N_2$, both rely on covalent bonds. In water ($H_2O$), two hydrogen atoms share one electron with oxygen, so oxygen sees 10 electrons. The most versatile of all covalently bonded elements is element 6, carbon (chemical symbol C). As with ionic and metallic bonding, the properties of materials with covalent bonds reflect the behavior of the electrons. All common liquids and gases form from small, covalently bonded molecules of just a few atoms. Because electrons are localized in the vicinity of a few atoms, covalently bonded compounds are usually poor electrical conductors, or to put it another way, they are very good electrical insulators.

In the next lecture, we will explore the amazing versatility of the covalent bond. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 9.

## Supplementary Reading

Snyder, *Extraordinary Chemistry of Ordinary Things*, Chapters 2–3.

## Questions to Consider

**1.** Think about a universe with a different set of magic numbers (electron arrangements of extreme stability), with other arrangements much less stable. Can you imagine any bonding strategies other than ionic, metallic, and covalent?

**2.** Why should small covalently bonded molecules like nitrogen, oxygen, and water tend to form gases and liquids?

# The Chemistry of Carbon

## Lecture 22

**In this lecture, I'm going to focus on the chemistry of carbon, which is by far the most interesting, the most versatile, of all the chemical elements. This versatility follows from the great principle of carbon chemistry; that is that carbon forms strong, covalent bonds with itself as well as many other elements.**

Chemical bonds reflect the tendency of atoms to attain a filled outer electron shell with 2, 10, 18, 36, 54, or 86 electrons. While there are only three major types of chemical bonds, and only a few dozen common elements, an endless variety of chemical compounds can be formed. The element carbon, because of its unparalleled ability to form covalent bonds, is extraordinary in this regard. More than 90% of all known compounds contain carbon, and the study of carbon chemistry, called organic chemistry, is the major focus of modern chemical research.

The geometry of carbon bonding is governed by the sixth element's need for four additional electrons, provided by surrounding atoms. First, consider the varied compounds of carbon and hydrogen—the hydrocarbons. Methane ($CH_4$), with four neighboring hydrogen atoms, is the simplest hydrocarbon. A key reason for the variety of carbon's chemistry lies in the fact that it can easily bond to itself. Thus, a C-C bond can substitute for one or more of the C-H bonds in methane to give the flammable gas ethane ($C_2H_6$). $C_3H_8$ is propane. In diamond, every carbon atom is linked to four others in a strong three-dimensional framework. Normal alkanes include a large series of covalently bonded compounds with long, straight C-C-C-C-… backbones, surrounded by hydrogen atoms. Butane ($C_4H_{10}$) and propane ($C_3H_8$) are examples of alkanes.

Hydrocarbons can also have branches. The simplest branched hydrocarbon is isobutane, with a T-shaped arrangement of four carbon atoms. Normal butane and isobutane are isomers of $C_4H_{10}$. As the number of carbon atoms increases one by one, the number of isomers increases exponentially. Alkanes with 20 or more carbons have thousands of isomers. Isomers are those compounds

with the same chemical composition but different molecular structures. Octane (with 8 carbons) has 18 isomers, one of which defines gasoline's octane rating.

In cyclic hydrocarbons, carbon atoms form one or more rings. One common ring molecule is cyclohexane ($C_6H_{12}$), with a six-carbon ring. Ring hydrocarbons can also have branches, or additional rings, nested together or separated by chains in almost any imaginable arrangement.

Carbon can form a double bond with itself (C=C), so that two of the four electrons required by each carbon are shared. The simplest doubled-bonded hydrocarbon is ethene ($C_2H_4$), a member of the alkene series. All of the variations described above—chains, branches, and rings—can also feature double bonds. For example, benzene ($C_6H_6$) has three single C-C and three double C=C bonds. Carbon also occasionally forms a triple bond with itself, as in acetylene ($C_2H_2$), which is a member of the alkynes. All the rich variety of alkanes and alkenes is seen in alkynes.

The properties of hydrocarbons are closely related to their structures. All hydrocarbons burn, combining with oxygen to produce heat, plus water and carbon dioxide. The smallest molecules, with four or fewer carbon atoms, are typically gases or volatile liquids, including propane ($C_3H_8$) and butane ($C_4H_{10}$). Larger straight-chain molecules are more massive and thus have progressively higher melting and boiling points. Branching and cyclic hydrocarbons usually have lower melting and boiling temperatures than straight isomers, because they don't pack as efficiently.

The chemistry of carbon becomes more complicated as additional elements come into play. Oxygen (element 8) needs two extra electrons, so it often forms a double bond with carbon. Formaldehyde ($CH_2O$) has three carbon neighbors, with the oxygen sharing a pair of electrons. In carbon dioxide ($CO_2$) each oxygen shares a pair of electrons. Oxygen atoms can also form part of a ring of atoms.

An OH, or hydroxyl, group, forms a single bond with carbon. Methanol ($CH_3OH$) is the simplest alcohol. Ethanol ($C_2H_5OH$) is the alcohol in beer, wine, and spirits. Formic acid, CHO(OH), is the simplest of the carboxylic

acids, which play key roles in the energy-producing chemistry of living things. Nitrogen (element 7) needs three extra electrons. It can therefore play a complex role in carbon-based compounds, substituting in chains, rings, or branches. In living things, sulfur and phosphorus add even more complexity to these amazingly diverse structures.

All of these carbon-based molecules are electrically neutral. These molecules bond together by the van der Waals attraction. When two molecules approach each other, every electron and proton in one molecule experiences an electrostatic force from every electron and proton in the other. Electrons in both molecules shift positions slightly as a result. This deformation of electrons may result in a small attractive force between the molecules—the van der Waals attraction. Some common layer minerals, including talc (baby powder) and the graphite in your pencil, are held together by van der Waals attraction between the layers.

Polymers, including synthetic fibers such as nylon and rayon, paints and glues, foam insulation, plastics, and many biological materials, are among the most useful organic molecules. Polymers begin as a liquid solution of monomers, which are small carbon-based molecules. The monomers of nylon are two similar six-carbon-chain molecules. When these chemicals are mixed, strong flexible fibers can be pulled from the solution.

Plastics form from complexly intertwined polymer strands. The hardness and flexibility of a polymer depends to a great extent on the cross-linking between these strands. Covalent cross bonds may form if the original monomers are branched.

Another important type of cross-linking in plastics is hydrogen bonding. A hydrogen atom on the outside of an organic molecule often develops a slight positive charge, while other atoms such as oxygen have a slightly negative local charge. Hydrogen bonds form from the attraction between the slightly positive hydrogen atoms and exposed atoms on other molecules. Individual hydrogen bonds are weak, but plastic-forming molecules contain an abundance of hydrogen, and thus polymers typically have numerous hydrogen bonds. The strength of many hydrogen bonds gives ice—solid $H_2O$—its hardness.

We will revisit some of these vital materials when we discuss physical properties, and again in introducing the molecules of life. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 9.

## Supplementary Reading

Snyder, *Extraordinary Chemistry of Ordinary Things*, Chapters 7–8, 20–21.

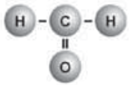
## Questions to Consider

**1.** Different isomers of an alkane are compositionally identical. Why should they have different physical properties?

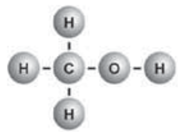
**2.** Why do organic chemists say that the number of possible carbon-based molecules is, for all intents and purposes, infinite?

# The Chemistry of Carbon

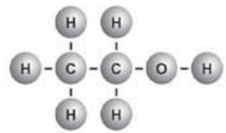
Formaldehyde $CH_2O$



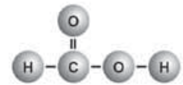
Methanol $CH_3OH$



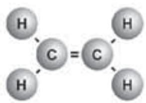
Ethanol $C_2H_5OH$



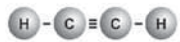
Formic Acid CHO(OH)



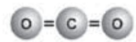
Ethene $C_2H_4$



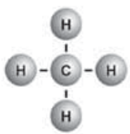
Ethyne or Acetelyne $C_2H_2$



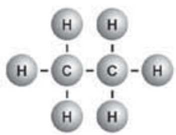
Carbon Dioxide $CO_2$



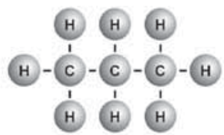
Methane $CH_4$



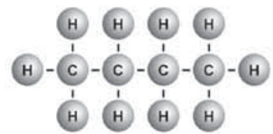
Ethane $C_2H_6$



Propane $C_3H_8$

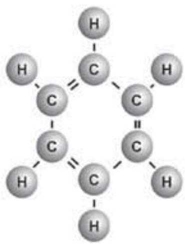


Butane $C_4H_{10}$

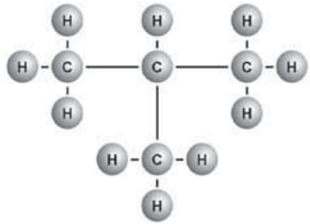


# The Chemistry of Carbon

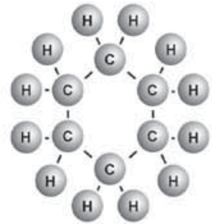
Benzene $C_6H_6$



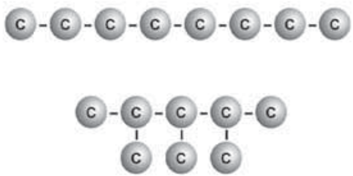
Isobutane $C_4H_{10}$



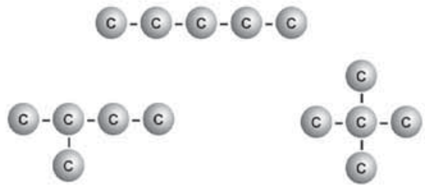
Cyclohexane $C_6H_{12}$



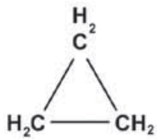
Isomers of Octane



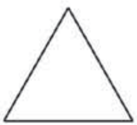
Isomers of Pentane



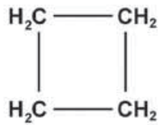
# The Chemistry of Carbon



Cyclopropane

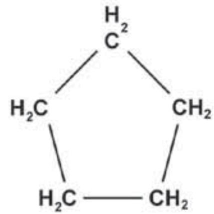


$C_3H_6$

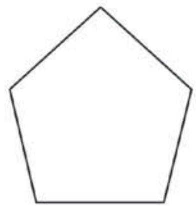


Cyclobutane

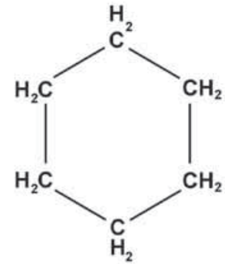
$C_4H_8$



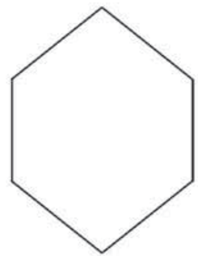
Cyclopentane



$C_5H_{10}$



Cyclohexane



$C_6H_{12}$

# States of Matter and Changes of State

## Lecture 23

**I'll be switching attention from the focus on individual atoms and small molecules to the collective behavior of atoms and molecules, the properties of the materials in our everyday world. A great principle of material science, one that we experience every day, is that the temperature and pressure induce changes in the state of chemical compounds.**

Atoms in combination display distinctive physical and chemical properties. The behavior of our planet, indeed the presence of life itself, depends on the coexistence of different states of matter. The states of matter—solid, liquid, gas, and plasma—are an everyday manifestation of the submicroscopic organization of atoms and molecules.

Solids have a more-or-less fixed shaped as a consequence of a three-dimensional arrangement of relatively strong, directional bonds. In crystals, atoms occur in regularly repeating patterns. In table salt, for example, that pattern is a tiny cube, a billionth of an inch on a side, with sodium and chlorine atoms. Many common materials, including gemstones, beach sand, and computer chips are found as single crystals. Most metals, rocks, concrete, and pottery are polycrystalline, formed of many tiny, interlocking crystals. Glass is a general term for a solid that does not have a regular crystal structure. In most glasses, the local atomic environment is quite predictable, but the arrangement of next nearest atoms is not so regular. Plastics are solids formed from polymers. As a result, plastics have a predictable structure in one dimension along the polymer chain but a less orderly arrangement between the complexly intertwined chains.

Composite materials, including plywood, reinforced concrete, and bone, combine two or more crystalline, glass, or polymer components; the materials' properties thus surpass those of the individual components. Reinforced concrete is another example of a solid composite material.

Liquids are collections of atoms or molecules that can change shape while retaining their volume. At the molecular scale, liquids behave something like a bag of flour or sugar. Forces hold the particles of the liquid together, but they are free to move past each other. Forces between molecules in a liquid lead to surface tension, which causes drops to form. Water is the only very common liquid in nature and plays a key role in life on earth. Liquid crystals are composed of polar molecules, in which one end adopts a slightly positive charge and the other end a slightly negative charge in an electric field. When the electric field is off, they act like a normal liquid with randomly oriented molecules, but when the electric field is turned on, all the molecules align themselves like a bunch of compass needles. This change alters the liquid's appearance. Liquid crystal displays used in watches are an example.

**Temperature and pressure induce changes in the state of chemical compounds.**

A gas is a collection of atoms or molecules that expands to fill the available volume. Inert gases are composed of individual atoms. Other gases ($O_2$, $CO_2$, $NH_3$, for example) are formed from small molecules. Gas pressure is the result of collisions between these particles and the container. When a gas is subjected to extremely high temperatures, the collisions become so energetic that some electrons are stripped off. The atoms and molecules become ionized, and the resulting state of matter is called a plasma. Plasma, which forms stars, is the most common state of matter in the universe. Fluorescent light bulbs are an everyday example of plasma at work.

Matter can change state between solid, liquid, and gas. These transformations, including freezing, melting, boiling, and condensing, are most commonly observed as a result of changing temperature. Water is a liquid at room temperature; it transforms to a solid in a freezer and to a gas when heated. At temperatures of thousands of degrees, water, like most other substances, becomes a plasma. These changes are a consequence of changing rates of molecular vibration. We are fortunate that our planet maintains most of its water in the liquid state.

A candle provides a more subtle example of the same thing. Candle wax is solid at low temperature. At hotter temperatures, but still below 100°C, candle wax melts and saturates the wick with liquid wax. At the hottest point, where you see the bright flame, wax boils and burns.

Petroleum refining makes use of temperature to separate different kinds of molecules from crude oil. Distillation (or “cracking”) towers enable us to extract propane, butane, natural gas, and even asphalt from crude oil.

Changes of state can also result from changes in pressure. Pressure is defined as a force acting on an area. Pressure is generated by pushing a button or hammering a nail. The uniform high pressure that a diver experiences is called hydrostatic pressure. The atmosphere exerts hydrostatic pressure of 14.7 pounds per square inch at sea level. Pressures much less than 14.7 pounds per square are called partial vacuums. At lower pressure, water boils at lower temperature. At about 10,000 atmospheres, water freezes at room temperature. The dense form of ice at high pressure is different from the common ice used in drinks.

Scientists study high pressure using a device called the diamond anvil cell. Samples are confined between the flat tips of two gem diamonds. Diamond cells are now able to reach pressures of millions of atmospheres—greater than at the center of the Earth. Every substance becomes solid at sufficiently high pressure.

The variation of the states of matter with temperature and pressure can be illustrated on a phase diagram. The phase diagram of water shows that, at any given combination of temperature and pressure, water is either a solid or a liquid or a gas. Along certain lines, two states coexist—solid and liquid coexist along the melting line (0° C), for example. At one specific temperature and pressure, called the triple point (374°C and 220 atmospheres), solid, liquid, and gas all coexist together. The most astonishing effects of high pressure and temperature are phase transformations, where one solid form turns into another. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 9.

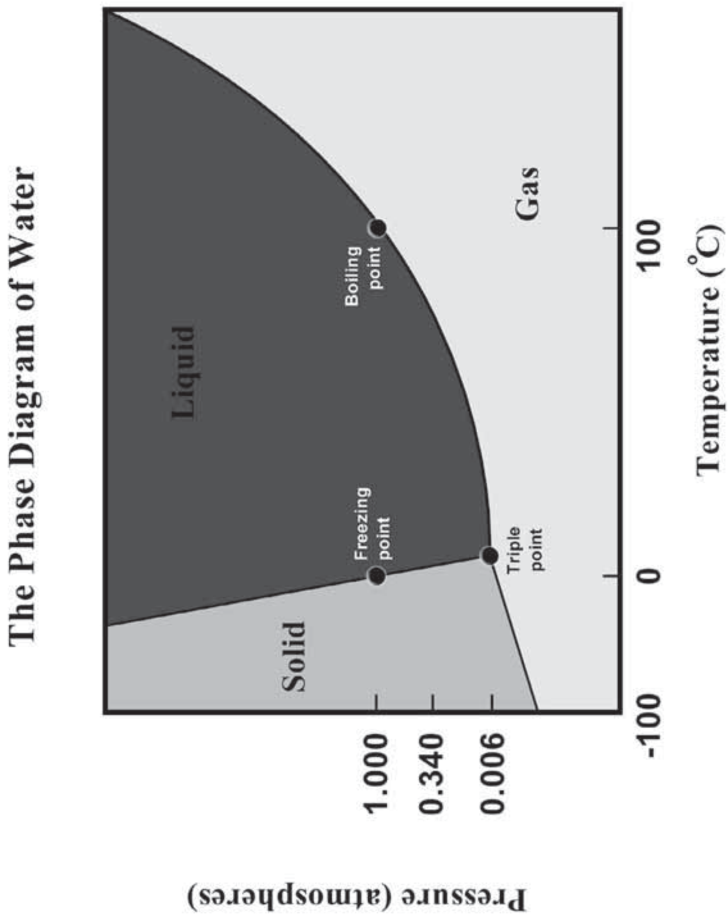
## Supplementary Reading

Hazen, *The New Alchemists*, Chapters 11–14.

## Questions to Consider

**1.** Think about an icy sidewalk on a cold winter day. How might you change the state of the ice without using temperature?

**2.** In what ways do you rely on pressure in everyday life?



The Phase Diagram of Water
Pressure (atmospheres)
1.000
0.340
0.006
-100
0
100
Temperature (°C)
Solid
Liquid
Gas
Freezing point
Triple point
Boiling point

# Phase Transformations and Chemical Reactions

## Lecture 24

**I'm going to introduce two major aspects of chemical change. The first topic is phase transformations. This is the property of some materials to alter their atomic structure when they are subjected to heat, or subjected to pressure, or some other external influence. … Then I'm going to introduce some of the many kinds of chemical reactions by which one group of elements and compounds transforms to chemical substances with totally new properties.**

Many common substances occur in more than one arrangement of atoms. The change of a substance from one atomic arrangement to another, particularly from one solid form to another, is called a phase transformation. Carbon, which occurs naturally both as graphite and diamond, provides a dramatic example of a phase transformation. Soft, black graphite is used as a lubricant and in pencil lead, while colorless diamond is the hardest known material.

More than 200 years ago, scientists began to explore ways to transform common graphite into rare diamonds. The key to synthesizing diamonds came in the 1870s from the discovery of South African diamonds embedded in their host rock, kimberlite. Geologists quickly realized that diamonds come from great depth in the Earth and that pressure is a key to their synthesis. Using theories that relate a material's structure to its stability, scientists were able to calculate a phase diagram for diamond and graphite. For decades, many people tried and failed spectacularly in their attempts to synthesize diamond from graphite at high pressure. In 1954, a team of scientists at General Electric succeeded in making the first synthetic diamonds. Today, over one hundred tons of synthetic diamonds are produced each year for use in a wide variety of commercial and industrial applications.

Not all phase transformations result in such drastic changes of crystal structure. One of my very first research projects used a diamond anvil cell to study the structure of the bright red mineral gillespite, a barium copper silicate. At high pressures of about 20,000 atmospheres it suddenly

transforms to a deep blue color. The color is due to a quantum jump of an electron in iron. A slight shift in atoms changes the energy of the quantum jump, and thus the mineral's color.

The most dramatic phase transitions of many compounds occur at extremely high pressure, where scientists expect all compounds to transform to metals. Electrons will delocalize under this condition, and the compound thus becomes a metal (a "sea of electrons"). Sulfur and oxygen have already been turned into metals in this way. High-pressure research holds the promise of producing thousands of new materials.

**Elements and compounds combine in chemical reactions to form new materials.**

A chemical reaction occurs when two different chemicals combine to form a different compound, or when one chemical breaks down to other substances. Even with only about 80 common chemical elements, there are 3,160 potential 1:1 two-element combinations, millions of combinations with different element ratios, and countless trillions of combinations when more elements are used. The art of chemistry is to predict which chemical combinations, at which synthesis conditions, will produce something new and useful.

All chemical reactions involve the rearrangement of electrons through the breaking and reforming of chemical bonds. Most reactions fall under a few general types. Oxidation-reduction reactions include many of the common reactions with oxygen, a highly reactive gas that forms about 20% of the atmosphere. Oxidation reactions occur when oxygen (or any other element that is eager to accept electrons) reacts with an electron donor, such as a metal. The chemical reaction called rusting, for example, involves the oxidation of iron metal:

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3$$

Burning is a more rapid form of oxidation, commonly involving hydrocarbons or other carbon-rich fuel. Fluorine is the strongest oxidizing agent known; it will rapidly oxidize almost anything it touches. Reduction is the opposite of

oxidation. Here oxygen gives up electrons and is "reduced," and the reacting element or compound gains electrons. Reduction reactions do not normally occur spontaneously in an oxygen-rich atmosphere, but sometimes they can be initiated in a hot fire. Iron oxide ores used to be smelted in such a fire by mixing the ore with lime (calcium oxide) and hot-burning charcoal in a furnace.

All oxidation-reduction reactions involve the movement of electrons. This leads to the mnemonic "OIL RIG": Oxidation is Lose, Reduction is Gain. Batteries rely on this transfer of electrons. The negative terminal of a battery is in contact with a chemical such as zinc metal, which readily gives up electrons and enters solution as $Zn^{2+}$ ions. Zinc becomes oxidized as the battery works. The positive terminal of the battery is in contact with a solution containing copper ions ($Cu^{2+}$) that readily accepts electrons. Copper becomes reduced and is deposited as copper metal on the positive terminal. When a circuit with a battery is closed, electrons flow from the battery's negative terminal, through the circuit, to the positive terminal. The battery goes "dead" when all the electron donors and electron acceptors have been used up.

Life obtains its energy from oxidation-reduction reactions. Plants take in carbon dioxide and water and use the energy in sunlight to reduce them. Animals gain energy by oxidizing sugars and other chemicals produced by plants.

Many other kinds of chemical reactions occur in everyday life. Water and many other liquids have the ability to cause solution and precipitation reactions. Salt dissolves in fresh water, for example, while a saturated salt-water solution at high temperature will precipitate salt crystals as it cools. Classic wet chemical analysis involves a careful sequence of solution and precipitation reactions.

Acids and bases are chemicals that alter the properties of water-based solutions. An acid is any chemical that produces positively charged hydrogen ions when added to water. Bases include chemicals that produce negatively charged hydroxol ($OH^-$) ions when put in water. When mixed together, acids

and bases tend to neutralize each other by forming water molecules. The strength of an acid or base can be measured by the pH scale.

Polymerization reactions play a vital role in modern life. Polymers form from smaller molecules, called monomers, in two common ways. Addition polymerization occurs when the monomers just join together, end-to-end. Condensation polymerization releases a molecule, such as $H_2O$ or $CO_2$, for each new monomer added.

Some polymerization reactions, like superglue or paint hardening, occur spontaneously. Other such reactions, like cooking an egg, require heat. The breakdown of a polymer into smaller molecules is called a depolymerization reaction. Cooking and marinating are common methods of depolymerizing meat, which has tough polymer fibers in its raw form. Cooking also depolymerizes the fibers that give many plant stems and leaves their rigidity. Museums often have to work hard to prevent the depolymerization of historic documents, cloth, leather, and other polymer-based artifacts.

We'll return to chemical reactions in a few lectures, when we begin to examine the chemistry of life. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black*, Chapter 4.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 9.

## Supplementary Reading

Hazen, *The New Alchemists*, Chapters 1–10.

Hoffmann, *The Same and Not the Same*.

Snyder, *The Extraordinary Chemistry of Ordinary Things*, Chapters 6, 10–11.

## Questions to Consider

1. Think about what happens when blood clots. Is clotting a change in state or a chemical reaction? Why?

2. Identify three different chemical reactions that you have observed in the past day.

# The Joy of Science (Lectures 25–36)

**Scope:**

Thus far we have explored the great overarching principles of physics and chemistry—the laws that describe the behavior of matter, energy, forces, and motions, as well as the nature of atoms, singly and in combination. In Part III of this lecture series, we turn from these general principles to the study of specific physical systems. These principles are manifest in the properties and behavior of materials, notably the variety of electronic materials (Lectures 25 and 26), as well as in the characteristics of isotopes and their energy-producing nuclear reactions (Lectures 27 and 28).

Astronomy (Lectures 29 and 30) is the study of distant objects, including stars—systems that must be studied by collecting their photons. Stars begin their lives as immense balls of hydrogen, which they gradually convert to helium and other elements by nuclear reactions. At the largest scale of the universe are galaxies (Lecture 31), which are vast collections of billions of gravitationally bound stars. Studies of galaxies provide evidence for the big bang theory of the origin of the universe (Lecture 32). Studies of universal origins are also guided by physicists' efforts to develop a "theory of everything," which unifies the structure of matter and forces (Lecture 33). Our own solar system formed from a swirling cloud of dust and gas called a nebula (Lecture 34). The orbital properties and chemical compositions of the Earth and other planets reflect their origins in the solar nebula (Lectures 35 and 36). ■

# Properties of Materials

## Lecture 25

**In this lecture, after a brief review of what I mean by "properties of materials," I'm going to consider five critical kinds of properties that occur in the materials of our everyday world. These five properties are strength, thermal expansion, stickiness, magnetic behavior, and electrical conductivity.**

Materials are useful because of their distinctive properties: color, hardness, flexibility, density, transparency, texture, electrical conductivity, thermal expansion, melting and boiling points, heat capacity, and on and on. So important are materials that we define key periods in human history in terms of a predominant material: the Stone Age, the Iron Age, the Bronze Age.

The modern age in human history is characterized by an astonishing variety of new materials. Your furnishings feature many different kinds of inorganic materials: metal alloys, specialty glass, and many kinds of ceramics. You probably own hundreds of different kinds of high-tech organic compounds: paints, glues, tapes, fibers, fuels, dyes, insulation, medicines, cosmetics, soaps, detergents, inks, and an amazing variety of plastic products from shopping bags to sneakers. Other materials of the electronic age are stereos and computers in an automobile. The distinctive properties of these and other materials are the result of the kind of atoms, their arrangement in three dimensions, and the way they are bonded together.

**The properties of a material depend on the type and arrangement of its atoms.**

Strength and hardness are important material properties. Materials scientists distinguish three different kinds of strength: compressive, tensile, and shear. Compressive strength refers to a material's resistance to being crushed. Materials with high compressive strength must have rigid frameworks of atoms. Soft or weak materials have one or more planes of atoms with weak bonds.

Tensile strength refers to a material's resistance to being pulled apart. Materials with high tensile strength must have continuous chains of strongly bonded atoms or molecules. Even a few damaged bonds can destroy a strong nylon rope.

Shear strength refers to a material's resistance to being twisted. Materials with high shear strength require a structure with strong triangular cross-bracing, like a trestle bridge. The structure of diamond leads to its exceptional shear strength.

The three types of material strength do not always go hand in hand. In many applications, a combination of these three different kinds of strength are required. These considerations come into play particularly in designing structures to withstand earthquakes. Earthquakes shake a building in several different ways—up-and-down, side-to-side, and twisting. Composite materials, including reinforced concrete and plywood, dramatically increase a building's combined compressive, tensile, and shear strength. Minor defects can drastically reduce a material's strength. For example, a small chip in a car windshield can eventually spread into a major crack.

Other physical properties are also closely tied to structure and bonding. Thermal expansion, the tendency of a solid or liquid to expand when heated, is also closely related to chemical bonding. In most heated materials, atomic vibrations cause atoms to bump into each other and push apart slightly. A few materials have negative thermal expansion. These compounds have three-dimensional frameworks of extremely strong ionic bonds that act like rigid sticks.

Stickiness is another important property. We want certain materials, such as inks, glues, and tape, to stick, while we want other surfaces, such as frying pans and our car's windshield, to be resistant to sticking. This property is a direct consequence of bonding at the material's surface. Sticky substances feature groups of atoms at their surfaces that readily bond with other substances. A current challenge in chemistry is to invent non-stick surfaces. For such a material to be effective, the outer layer of atoms must look to the world like a layer of inert gas, which bonds to nothing.

Magnetic materials are able to attract iron and other magnetic materials. Moving electrons cause magnetic fields, so electrons in orbit around an atom can produce a tiny dipole magnet. While the movements of different electrons effectively cancel each other out in many atoms, a few elements like iron, nickel, and cobalt are magnetic. The magnetic behavior of a material depends on the alignment of these individual atomic magnets. In a ferromagnetic material, many atoms may align to produce a large dipole field. Think about what happens when a magnet material is subjected to a magnetic field. Every atom is a tiny magnet, so a force is exerted on every atom and the atoms must move slightly. A solid magnet will actually change shape slightly in this situation. One of the most common applications of magnets in everyday life is in speakers and microphones.

One of the most important properties of materials in modern life is their ability to control the flow of electricity. Electrical conductors and insulators are both essential to this process. Good electrical conductors include all materials in which electrical charges flow easily. The most common conductors are metals, such as copper or aluminum, which by definition have electrons that are free to move under the slightest voltage.

Fast-ion conductors are a growing class of materials with special applications in batteries. These materials have atomic-scale channels, like pipes, through which ions (charged atoms like $Na^+$ or $Cl^-$) will flow under an electric field. Many polymer scientists are trying to develop conducting carbon-based polymers that might someday replace metal wires.

Insulators are essential to restrict the flow of electricity, for efficiency and safety. The best insulators have strong ionic bonds, because every electron is "assigned" to a specific atom. Plastics, with covalent bonds, are not as effective insulators as ceramics, but they are more than adequate for low-power situations.

Superconductors are remarkable materials that conduct electricity without any resistance at all. Such a property—electricity with absolutely no resistance—suggested many practical applications, from powerful, permanent electromagnets to no-loss electrical power transmission. Superconductivity was discovered by the Dutch physicist Heike Kamerlingh-Onnes in 1911,

when he measured zero resistivity in a sample of mercury at 4 K. All of these materials require extremely cold temperatures to work. Most subsequent research focused on finding other superconducting metals, and eventually resulted in an alloy of the metal niobium that superconducts at about 22 K. This metal finds widespread use in high-power electromagnets, such as those used in magnetic resonance imaging (MRI) medical facilities.

In 1986, the first of a new class of superconductors that works at much higher temperature was discovered. I was involved in determining the crystal structures of some of the first of these high-temperature superconductors. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 10.

## Supplementary Reading

Amato, *Stuff*.

Gordon, *The New Science of Strong Materials*.

Hazen, *The Breakthrough: The Race for the Superconductor*.

## Questions to Consider

1. Imagine a useful material with a combination of properties that does not now exist. (This is how many chemists make a living.)

2. Write a list of materials that might be found in a home in America in 1776. If you lived under those conditions, what would you miss most?

# Semiconductors and Modern Microelectronics

## Lecture 26



**I am going to continue to examine the electronic properties of materials and focus on what many commentators think are the defining materials of our modern age: semiconductors.**

Every electrical circuit requires conductors that carry electricity efficiently and insulators that prevent the flow of electrons. But if those were the only materials we had, the world of electronics would be quite limited. We could light our rooms and heat our food with insulators and conductors. But the wonders of the electronic age—computers, cellular telephones, CD players, and countless other applications—would not be possible without semiconductors.

Modern semiconductors are exquisitely refined materials that conduct electricity, but not very well. Most modern semiconductors begin with a crystal of the element silicon. Each electrically neutral silicon atom holds 14 electrons, so it has a half-filled outer shell. In a silicon crystal, each atom shares four electrons with neighboring atoms, so every atom enjoys a full complement of 18 electrons. Silicon is a poor conductor of electricity, because all electrons have a stable local environment.

The properties of silicon change if a few atoms of phosphorus (element 15) substitute for a few silicon atoms. Each neutral phosphorus atom has 15 electrons, including 5 electrons in its outer shell—one more than is needed to give all the surrounding atoms a filled shell. This extra electron becomes delocalized, like the electrons in a metal. By adding about one atom in a million phosphorus impurity to a silicon crystal, a controlled number of mobile, negatively charged electrons becomes available. The result is an n-type semiconductor.

The same logic applies to a silicon crystal in which atoms of aluminum (element 13) substitute for a few silicon atoms. Each neutral aluminum atom has 13 electrons, including 3 electrons in its outer unfilled shell—one fewer than needed to give the surrounding atoms a filled shell. Missing electrons

are called holes, which carry a positive charge. By adding a small fraction of aluminum atoms to a silicon crystal, a controlled number of mobile, positively charged holes become available. The result is a p-type semiconductor. A huge, crowded parking lot serves as a metaphor for the contrast between an n-type and a p-type semiconductor. From a materials point of view, n- and p-type semiconductors are quite remarkable. Unlike most metals and insulators, n- and p-type semiconductors must be engineered atom-by-atom. Engineers in Silicon Valley use ultra-clean, high-vacuum devices to vaporize and deposit atoms on a flat surface.

A single chunk of n-type or p-type semiconductor, by itself, is a poor conductor of electricity. New phenomena arise when two or more pieces are grown together to form a composite material of both n- and p-type materials. A diode is a piece of n-type semiconductor joined to a piece of p-type semiconductor. Wires are attached to the two sides. Electric current that flows into the n-type side of the diode is attracted to the positive p-type side and continues through the diode. Current that flows into the positive side will not continue on into the negative side. The diode thus acts like a one-way valve for electricity. When you plug an electronic device into the wall, the first thing the electricity sees is often a diode. The next device the electricity sees is a capacitor (also called a condenser), which acts as a quickly rechargeable battery. A capacitor converts AC power from outside the equipment to DC power inside the equipment.

**Modern electronics rely on semiconductors, which control the movement of electrons.**

Other semiconductor devices incorporate more than two pieces of n- and p-type materials. The transistor is a three-layer sandwich of semiconductor material, either n–p–n or p–n–p. Transistors find many uses in modern electronics, especially as amplifiers and as logic circuits. The transistor created a revolution in electronics. The heart of many modern appliances is the microchip, or integrated circuit, which is a single semiconductor device that may incorporate thousands of transistor-like regions.

A computer is a machine that processes information. All modern computers rely on integrated circuits to store information and to manipulate that information. All kinds of information can be stored, transferred, and modified by a computer. Information can be converted into binary digits, or bits. A bit has two possible states: on and off, for example. Any kind of information can be reduced to bits (represented by "0" and "1"). The 26 letters of the alphabet plus common punctuation, similarly, could be specified by a five-digit sequence. Thus, entire libraries can be reduced to binary code. Illustrations are digitized (converted into a sequence of digits) by reducing them to a large number of pixels.

Computers are designed to store and process numerical information. Typical computers store most of their memory, typically billions of bits, on magnetic storage devices. On these devices small magnetic areas are oriented with north poles in two different possible orientations (north up or north down) to represent the bit. Computations are carried out in the computer's central processing unit—the CPU—which is typically one or more integrated circuits made of silicon-based semiconductors. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 10.

## Supplementary Reading

Amdahl, *There Are No Electrons*.

## Questions to Consider

1. Identify 10 objects in your home that use semiconductors. How old are they, and how obsolete compared to similar items now available?

2. How have computers affected your life, in both positive and negative ways?

# Binary Code

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | = 0 | 0 | 1 | 0 | 1 | = 5 |
| 0 | 0 | 0 | 1 | = 1 | 0 | 1 | 1 | 0 | = 6 |
| 0 | 0 | 1 | 0 | = 2 | 0 | 1 | 1 | 1 | = 7 |
| 0 | 0 | 1 | 1 | = 3 | 1 | 0 | 0 | 0 | = 8 |
| 0 | 1 | 0 | 0 | = 4 | 1 | 0 | 0 | 1 | = 9 |

# Isotopes and Radioactivity

## Lecture 27

**I'm going to begin this lecture by reviewing the nature of the atom and its nucleus. The nucleus has two kinds of particles, the protons and the neutrons. Then I'm going to introduce the concept of an isotope; an isotope is an atom in which we know both the number of protons and the number of neutrons.**

As scientists of the late 19th century explored the properties of elements and compounds, they discovered the unexpected ability of certain elements to give off radiation spontaneously. The discovery of radioactivity, and the subsequent exploration of the atomic nucleus, eventually led to the fields of nuclear physics and nuclear chemistry. Recall from Lecture 17 that Ernest Rutherford discovered the nucleus of the atom by firing what we called atomic bullets at gold foil. The unexpected recoil of some of those bullets suggested to Rutherford that atoms contain a small, massive, positively charged nucleus.

Protons are positively charged nuclear particles with a mass about 1,836 times the mass of an electron. The number of protons in an atom is the atomic number—the atom's position in the periodic table. Single isolated protons are also called hydrogen ions ($H^+$), since the hydrogen atom has one proton and one electron. Isolated protons are stable particles.

The discovery that atoms typically have more than twice the mass of the electrons plus the protons led scientists to speculate about the existence of another massive nuclear particle—one that has no electrical charge. The neutron was finally discovered in 1932, when the British physicist James Chadwick conducted experiments similar to those of Rutherford. Chadwick found that the neutron is, indeed, electrically neutral, which makes it difficult to detect. The neutron has a mass that is slightly greater than the proton. Isolated neutrons are not stable. They spontaneously transform into a proton and an electron, releasing energy in the process. While the number of protons is fixed for any given element, the number of neutrons can vary.

Think about how atoms are named. The number of protons defines the element name. Any atom with 6 protons is carbon. The number of protons and electrons defines the ion. A carbon atom with 5 electrons is $C^{+1}$. The number of protons and neutrons defines the isotope. A carbon atom with 6 neutrons is carbon-12, with 7 neutrons is carbon-13, and with 8 neutrons is carbon-14. The isotope number indicates the total number of protons and neutrons. $Fe^{56}$ is a special isotope of iron that we will study later. Protons determine the chemical behavior of an element because they are positively charged and thus attract electrons. Neutrons play no significant role in chemistry, but they play a decisive role in nuclear physics.

**Radioactive atoms spontaneously release energy in the form of high-energy radiation.**

All known combinations of protons and neutrons in an atomic nucleus are summarized in the table of the isotopes. The table lists the number of protons on the vertical scale and the number of neutrons on the horizontal scale. There are about 2,000 known isotopes shown on the table. For lighter elements, the numbers of protons and neutrons are usually similar, but heavier elements have more neutrons than protons. Positive protons repel each other, and neutrons act as spacers in the nucleus.

Isotopes can experience several different fates. Most atoms are stable isotopes—atoms whose nuclei will remain unchanged for billions of years. Isotopes can be altered in highly energetic nuclear fission and fusion reactions, as we shall see in the next lecture. About one in a million atoms is radioactive. These atoms can transform as a result of spontaneous changes in the nucleus. The nuclei of radioactive isotopes change spontaneously, while emitting high-energy radiation. Radioactivity was discovered by accident by the French chemist Antoine Henri Becquerel (1852–1908).

Prints and Photographs Division, Library of Congress.

**Henri Becquerel, discoverer of radioactivity.**

Of the several chemists who attempted to isolate the radiation-producing substance, the most successful was Maria Sklodowska Curie (1867–1934), who was born in Poland and spent much of her career in her husband Pierre's laboratory in Paris. The Curies refined tons of high-grade uranium ores from Bohemian mines. Eventually, in 1898, they extracted small quantities of the previously unknown elements polonium and radium. Marie Curie was awarded Nobel Prizes in both physics (1903) and chemistry (1911), the only person so honored. She died in 1934 of cancer that was undoubtedly caused by her extensive, cumulative exposure to high levels of radiation.

Research on radioactive elements from minerals led to the discovery of three distinct types of radioactivity decay. In alpha decay, an atom spontaneously releases a fast-moving particle composed of two protons and two neutrons. An alpha particle is the same as a helium-4 nucleus; it quickly picks up two electrons to form a helium atom. Ernest Rutherford first identified this radiation and subsequently used it as his atomic "bullets." After an alpha decay, an atom has two fewer protons and two fewer neutrons. Thus it transforms to a different element.

Beta decay produces high-energy electrons, or beta rays. In this process, a neutron spontaneously becomes a positive proton (which remains in the nucleus) and an electron (which flies off at near light speed). Isolated neutrons are radioactive and undergo beta decay; about half of them decay every 10 minutes. Each neutron becomes a hydrogen ion ($H^+$) and a speeding electron. Beta decay increases an atom's number of protons by one, thus changing the atomic number of the decaying atom. Some isotopes undergo gamma decay. They spontaneously emit extremely high energy electromagnetic radiation, called gamma radiation.

Take a closer look at the table of the isotopes. Every isotope is either stable or radioactive. Each radioactive isotope is characterized by a mode of decay—alpha, beta, or gamma—and a decay rate, called the half-life. The half-life is the time that it takes, on average, for half of a collection of that isotope to decay. Radioactive half-lives are the basis for radiometric dating.

When a radioactive isotope undergoes alpha or beta decay, a new isotope is produced. Often that isotope is also radioactive. One isotope decays to

another in a decay chain. $U^{238}$ is the most common radioactive isotope. Another isotope, $Ra^{232}$, is an inert gas, called radon. It is a carcinogenic health hazard which can enter houses through cracks in foundations.

The principal health concern regarding radioactive decay is that alpha, beta, and gamma rays are forms of ionizing radiation. Radiation can strip electrons off an atom, thus disrupting bonds. In living organisms, intense radiation can kill cells. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 11.

## Supplementary Reading

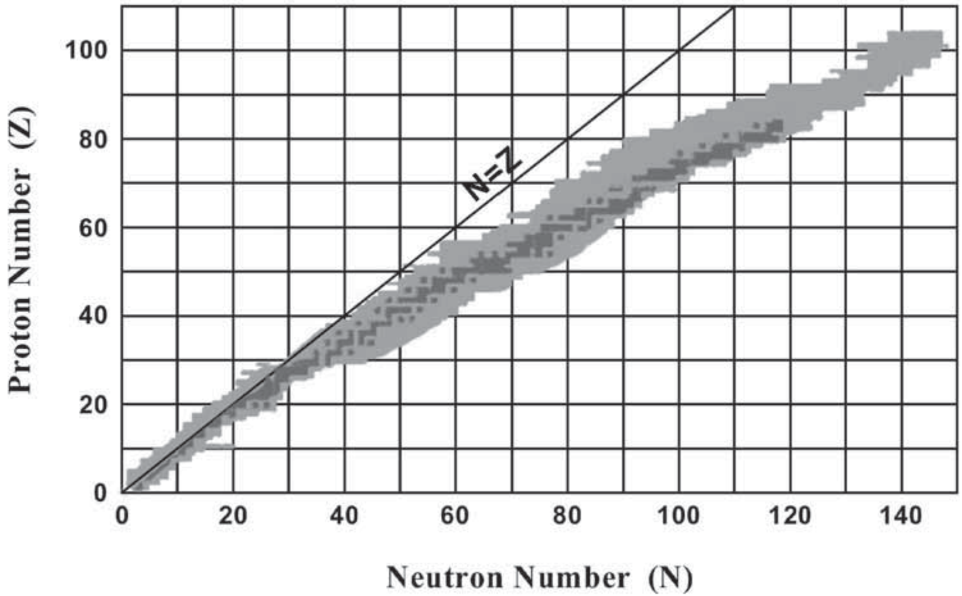
Pflaum, *Grand Obsession: Madame Curie and Her World*.

## Questions to Consider

1. Everyone is constantly exposed to radioactive elements—in air, in water, in soil, and in all building materials. What criteria, if any, should the government use to set safe exposure limits?

2. To what extent had Germany and Japan made progress toward making an atomic bomb in World War II? What factors limited their efforts?

## The Table of Isotopes



# Nuclear Fission and Fusion Reactions

## Lecture 28

**I'll focus on one of the transforming discoveries of the 20th century: the realization that nuclear reactions produce heat and radiation through the conversion of mass into energy.**

Isotopes can be either stable or radioactive, but they can experience other fates as well. When subjected to highly energetic environments, isotopes can fuse together or split apart, as they constantly do in stars. On Earth, scientists must help these processes along. The fact that some isotopes are stable and some are radioactive reveals that different isotopes have different nuclear potential energies. Like boulders perched on the sides of a steep-walled valley, some isotopes are ready to fall to lower energy states. Radioactive isotopes like uranium spontaneously release energy as radiation—energy that is quickly converted to heat. The mass of all the products of a nuclear decay is less than that of the original isotope; some mass is converted to energy.

Hydrogen also has a high amount of nuclear potential energy per atom; two hydrogen atoms can combine to form helium and energy. Iron-56 has the lowest nuclear potential energy of any isotope. It is the nuclear equivalent of ash. This is an important factor in star evolution.

Some heavy isotopes release prodigious amounts of energy when they are split apart in the process called fission. Fission can be triggered by a fast-moving particle such as a neutron. Uranium-235 can be split by a fast-moving neutron. The products from the original nucleus are two large chunks of roughly equal size, plus several high-speed neutrons. The two chunks are, themselves, new isotopes that are usually radioactive. The high-speed neutrons are available to split other uranium-235 isotopes. If the concentration of uranium-235 is high enough, a chain reaction will result. Each fission reaction triggers new reactions in a self-sustaining process.

A nuclear reactor is a device that controls a nuclear fission reaction. If the nuclear fuel is sufficiently concentrated, the chain reaction can proceed in an uncontrolled explosion—an atomic bomb.

In nuclear fusion reactions, two nuclei combine to form a single, larger nucleus. If the mass of the resultant nucleus is less than the original two nuclei, then energy will be released in the process. The most common fusion reaction in nature combines two hydrogen atoms to make a helium atom. This reaction is the primary energy-producing process in the Sun and most other stars. Under most circumstances, hydrogen atoms will not combine in this way, because positive charges of the two nuclei prevent the close approach of the atoms. Fusion occurs inside stars, where tremendous temperatures and pressures provide the energy needed to overcome the electrostatic repulsion.

**Nuclear reactions produce heat and radiation through the conversion of mass into energy.**

Nuclear fusion reactors would provide a sustained source of energy. The principal technical difficulty is creating a confined high-pressure, high-temperature environment. One strategy is to use a hydrogen plasma, which can be confined in a magnetic bottle and heated with electric current or high-intensity lasers.

The hydrogen bomb, developed shortly after World War II, also converts tritium (a radioactive isotope of hydrogen) into helium plus energy. Hydrogen bombs are triggered by atom bombs. There is no inherent limit to the size of a hydrogen bomb. Cold fusion was a much publicized, but failed, effort to produce fusion energy at room conditions.

Scientists use fusion techniques to produce artificial superheavy elements beyond the heaviest natural element, uranium (element 92). One technique is to bombard a uranium nucleus with slow neutrons. Eventually, the uranium atom becomes neutron-enriched, and it undergoes beta decay to the next higher element. The first artificial element, neptunium (element 93), was produced in this way at the University of California at Berkeley in 1940. Today, all the elements up to 112 have been created artificially by a variety of

techniques. These elements have been produced only in very tiny amounts; their half-lives are extremely short.

Nuclear technologies bring both benefits and problems. Among the most pressing problems associated with nuclear technology is nuclear waste disposal. This waste comes primarily from used reactor fuel rods and the byproducts of nuclear weapons production. Waste products of nuclear fission reactions include many radioactive isotopes with half lives as long as thousands of years. The problem of confining this waste for many thousands of years is compounded by decay chains: The mix of elements under storage keeps changing. The most widely accepted solution is burial in a dry, geologically inert environment.

Nuclear science has also brought benefits, in addition to its potential importance as a source of energy. Low-level radioactive tracers can be used to track groundwater, ocean currents, and air masses. In medicine, specific radioactive tracers highlight the workings of the body. Radioactive materials can also be used to destroy cancerous tissues. But by far the most important consequence of nuclear processes is the energy that Earth receives from the Sun. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 11.

## Supplementary Reading

Armbruster and Hessberger, "Making New Elements."

Herman, *Fusion.*

Rhodes, *The Making of the Atomic Bomb.*

## Questions to Consider

1. In what ways does the cold fusion story demonstrate the scientific method?

2. How would you react to having a nuclear waste repository in your state? Where should we put it?

# Astronomy

## Lecture 29

**We shift our focus from the subatomic nucleus to the largest continuous objects in the universe, stars. In spite of the extreme difference in scale in size, this is a logical segue, for stars are nothing more than giant nuclear-fusion reactors.**

Fusion, the process by which two hydrogen nuclei combine to form a helium nucleus plus energy, is the principal means of generating energy in the Sun and other stars. In this lecture we consider the nature of astronomical data that led to this profound discovery. Astronomy is an observational science, and virtually all of the information that we have about distant stars comes from photons—electromagnetic radiation that travels 186,000 miles per second through space. The art of astronomy is the collection, analysis, and interpretation of these data.

**Astronomy is the science (and art) of collecting, analyzing, and interpreting photons from space.**

Astronomers measure four aspects of photons coming from space.

- The wavelength, measured by spectroscopy.
- The intensity, measured by a device like a light meter.
- The direction, measured by two angles.
- The variation of wavelength, intensity, and position with time.

From these data, astronomers attempt to understand the spatial distribution, the dynamic state, and the past and future of the universe. A major challenge in astronomy is that the universe is three-dimensional, yet we see the stars almost entirely in two dimensions. The distance to an object can be measured by parallax (a form of triangulation) or from "standard candle" objects of

known brightness. The composition of a star can be determined from line spectra of the elements:

- The motion of a star can sometimes be measured by detecting absolute motion over long periods of time, or by the Doppler shift of light.
- The surface temperature of a star is determined from the star's color.
- The brightness or apparent magnitude of a star, combined with a knowledge of its distance, gives the total energy output of the star.
- The mass of a star can be deduced in part from its motion, but primarily from theoretical models.

Telescopes are photon collectors. The science of astronomy has gone hand-in-hand with the development of new telescopes. Many astronomers refer to the present as the golden age of observational astronomy, because we now have orbiting observatories to study the entire electromagnetic spectrum. Optical telescopes use a combination of lenses and mirrors to focus and magnify light from distant objects. The Hubble Space Telescope provides an unparalleled view of the universe in optical wavelengths. Old telescopes are often improved by installing new film or electronic detectors. Modern detectors can measure the signal from a single photon.

The atmosphere is largely transparent to radio waves and microwaves, so radio telescopes can be ground-based. Increasing interference from ground-based communication sources limits these devices. Much more sensitive detection was provided by the Cosmic Background Explorer (COBE), which was a satellite-based microwave observatory. Satellite observatories collect information on infrared, ultraviolet, X-ray, and gamma ray wavelengths.

Telescopes resolve billions of stars in the Milky Way galaxy (the collection of stars that includes the Sun) and countless more stars in other galaxies beyond. Some systematic sense can be made of the great variety of stars on a Hertzsprung-Russell diagram, which is a graph of surface temperature versus total energy output. A star's surface temperature is determined from the spectrum, or color, of the star. Blue-white stars are hotter and reddish

stars are cooler. Total energy output is determined by knowing the distance and apparent magnitude of the star. The Hertzsprung-Russell diagram makes no assumptions about a star's energy source, but intriguing patterns emerge as more stars are plotted.

The great majority of stars lie along a prominent curvy band down the middle of the diagram. Stars lying close to this line are called main sequence stars. Main sequence stars show a close relationship between temperature and energy output. Two other common groupings of stars fall well off the main sequence. In the upper right corner are red giant stars—relatively cool stars that give off huge amounts of energy because they are very large. At the bottom of the Hertzsprung-Russell diagram, by contrast, is a group of relatively hot stars with surprisingly low energy output, because they are very small.

The power of the Hertzsprung-Russell diagram is that it uses simple, measurable properties of stars to compare and contrast the variety of stars. In science, such systematic patterns are often the key to understanding the behavior of natural systems. Stars begin their lives as spheres more than 90% hydrogen, with a small fraction of helium and other elements. Astronomers soon realized that main sequence stars include stars of all sizes that obtain their energy through hydrogen fusion—a process called hydrogen burning.

Smaller stars generate less heat and pressure, and so the fusion process is slower. These stars fall in the lower right corner of the diagram. Larger stars have interiors at much higher temperature and pressure, and so the fusion process is rapid. These stars occupy the upper left portion of the diagram.

The hydrogen fusion process takes place in three steps.

- First, two protons fuse and quickly undergo a beta decay, to form a nucleus with one proton and one neutron.

- Second, a proton and deuterium fuse to form a helium-3 nucleus with two protons and a neutron.

- Third, two helium-3 nuclei fuse to form a helium-4 nucleus plus two protons.

The net result is that four protons have fused to form one helium-4 nucleus and lots of energy.

One consequence of hydrogen burning is the production of prodigious amounts of a subatomic particle called a neutrino. Neutrinos are supposedly massless particles that have no electrical charge and are thus difficult (but not impossible) to detect. Yet, when scientists attempt to measure these solar neutrinos, they observe only about one-third of the expected number. This situation is called the solar neutrino problem. One possible explanation is that solar neutrinos may "oscillate" into other particles that aren't detected. Particle theory says that such neutrino oscillations are only possible if neutrinos have mass. If true, then neutrinos may have a bearing on the ultimate fate of the universe.

Our Sun is a rather ordinary star, lying midway along the main sequence of the Hertzsprung-Russell diagram. As we shall see in the next lecture, the Sun and all other stars have a finite lifetime. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 14.

## Supplementary Reading

Ferris, *Coming of Age in the Milky Way*.

Jastrow, *Red Giants and White Dwarfs*.

Zeilik, *Astronomy*, Chapters 5–6.

## Questions to Consider

1. Should the United States government continue to use taxpayers' money to build space-based telescopes?

2. How is it possible that most solar neutrinos pass through the Earth? What properties must a particle have for it to pass through most matter?

# The Life Cycle of Stars

## Lecture 30

**I'm going to review the evidence that the life cycle of a star depends on its mass. … First, after reviewing the last lecture on stars, I'll begin by examining our own star, the Sun, in some detail. I want to give you a feeling for our special knowledge about this nearby star.**

The Sun cannot burn forever; day-by-day its mass is diminished. Studies of the Sun, combined with observations of the life and death of more distant stars, reveal the ultimate fate of our own solar system. It is a rather ordinary star, lying near the middle of the main sequence of the Hertzsprung-Russell diagram. Because of its proximity to us, the Sun is by far the most thoroughly studied star.

The Sun is a sphere of hydrogen almost 700,000 kilometers in radius. In cross-section, the Sun has several distinct layers. Most of the hydrogen burning takes place in the core, the central 10% of the Sun's volume. Energy is transferred from the core to the surface primarily by radiation in the deepest interior, and then by convection of the hydrogen-rich plasma in the outer 200,000 kilometers. We also learn about the Sun from its "solar wind," a constant stream of hydrogen and helium ions that stream outward and interact with the Earth's magnetic field.

**The life cycle of a star depends primarily on its mass.**

Our intimate knowledge of the Sun allows us to model the life cycles of different-size stars. Computer models reveal that the lives of stars are a constant battle between the force of gravity pulling inward and the radiative force of nuclear fusion pushing outward. These models merge information from many fields, including nuclear physics, plasma physics, and fluid dynamics. Modelers set up a system of equations that treat the Sun as composed of concentric uniform layers. They estimate a starting temperature, pressure, and composition for each layer, and

assume that the first law of thermodynamics holds for every layer—energy must be conserved.

The major conclusions of these models are now in close agreement. Four-and-a-half billion years ago, when the Sun formed, it was less bright—perhaps only 70% of its present energy output. The Sun will continue its hydrogen-burning stage for several billion more years, and it will continue to gradually increase in brightness.

The Sun has shone, and will continue to shine, for billions of years. Most stars lie on the main sequence, because they spend most of their lives burning hydrogen. Red giant and white dwarf stars suggest that other processes will eventually come into play.

All stars eventually run low on hydrogen fuel in their cores. In the final stages of the Sun's life, helium concentrations will build up in the core, and hydrogen burning will take place farther out. The increased hydrogen burning, closer to the Sun's surface, will cause the Sun to expand outward, engulfing Mercury and then passing the orbit of Venus. At some point during this dramatic transition, the Earth will become uninhabitable. The Sun will emit much more energy than now, but it will do so out of a much larger surface area. The surface, therefore, will cool and the Sun will become a red giant. Note that this process takes the Sun away from the main sequence, toward the upper right of the Hertzsprung-Russell diagram.

As a result of hydrogen burning around the core, the core gets hotter and all remaining hydrogen is consumed. Helium nuclei fuse to form heavier nuclei—notably, three helium-4 nuclei eventually become a carbon-12 nucleus—in the process of helium burning. Carbon is as far as fusion reactions in the Sun's core can progress. Once the core is carbon, the nuclear processes in the core slow down. With the outward radiation pressure turned off, the star begins to collapse under gravity, eventually shrinking to a white dwarf—a dense sphere about the size of Earth. Eventually, the total energy output of the Sun will be only a thousandth of its present value, but the Sun will be so small that surface temperatures will be tens of thousands of degrees. Slowly the Sun will cool as the residual energy floods out into space.

The smallest stars, about a tenth the size of the Sun, are called brown dwarves. These small stars burn their hydrogen very slowly and thus never get very hot or large. They lie on the main sequence since they burn hydrogen, but at the extreme lower right corner. Brown dwarves never get beyond hydrogen burning, and they continue to glow weakly for perhaps 100 billion years. Because brown dwarves are so faint, they are difficult to detect with ground-based telescopes.

Stars a few times more massive than the Sun experience a very different fate. A star ten times more massive than the Sun will burn its hydrogen fuel in perhaps 100 million years and will have several concentric layers of fusion reactions. As hydrogen- and helium-burning progresses, deep layers will produce progressively heavier elements—oxygen-16, neon-20, magnesium-24, all the way up to iron-56. The last of these steps can occur in a matter of minutes. Iron-56 is the ultimate nuclear ash. Under no conditions can nuclear energy be extracted from iron-56, either by fission or by fusion. When a star races through its final fusion stages to iron, the nuclear fires suddenly turn off. There is no force to counter the immense pull of gravity.

In an instant, the star collapses to form an intensely hot and dense mass that rebounds in an explosion of unimaginable power. Such an exploding star is called a supernova. Nuclei of all sizes are fused together to form every element of the periodic table. This matter is flung out into space in all directions to seed the galaxy with raw material for future stars. Stars are giant factories of the elements; starting with hydrogen, they synthesize everything else.

Often when a star explodes, it leaves behind a smaller object that marks the place of the former star. A mass more than several times that of the Sun will collapse into an incredibly dense object in which electrons and protons merge to form neutrons—just the reverse of beta decay. Such a neutron star might be 10 miles in diameter, with a mass greater than the Sun. Neutron stars rotate extremely rapidly, and they have strong magnetic fields that generate powerful radio signals as the star rotates. From Earth, these radio sources seem to pulsate thousands of times per second. Pulsars were first mistaken for a possible sign of alien life when they were discovered in 1962.

A mass more than about 30 times the mass of the Sun has such immense gravitational force that all mass collapses into a point, called a black hole. Nothing, not even light, can escape from a black hole. While black holes themselves are invisible, it is possible to see matter from adjacent stars streaming into one. Black holes also may be revealed by gravitational lenses that bend light coming from more distant objects. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 14.

## Supplementary Reading

Ferris, *Coming of Age in the Milky Way*.

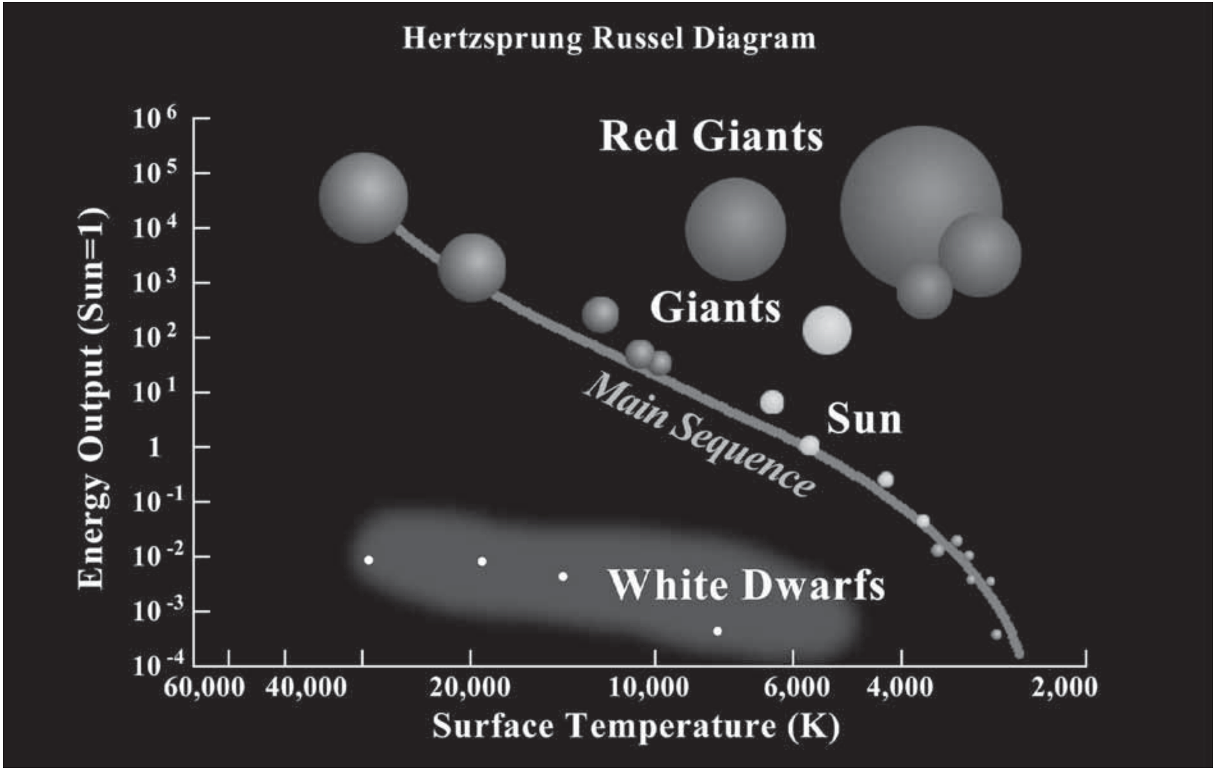
Jastrow, *Red Giants and White Dwarfs*.

Zeilik, *Astronomy*, Chapters 13–17.

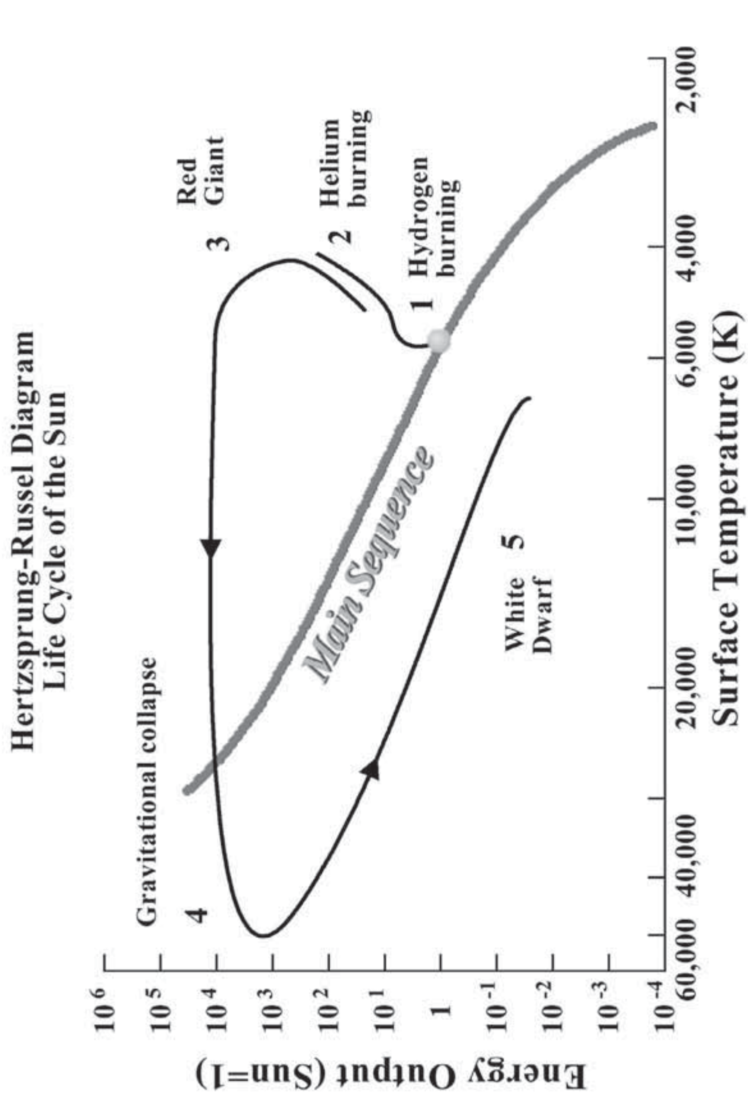
## Questions to Consider

**1.** How might our Solar System have been different if the Sun had been half its present size? Twice its present size?

**2.** If exploding stars are the only known source of the heavier elements, where did the gold or silver atoms in your jewelry come from? Try to imagine a history of such an atom.



Hertzsprung Russel Diagram
Red Giants
Giants
Sun
Main Sequence
White Dwarfs
Energy Output (Sun=1)
10 6
10 5
10 4
10 3
10 2
10 1
1
10 -1
10 -2
10 -3
10 -4
60,000
40,000
20,000
10,000
6,000
4,000
2,000
Surface Temperature (K)


Hertzsprung-Russel Diagram
Life Cycle of the Sun
Red Giant
3
Helium burning
2
Hydrogen burning
1
Main Sequence
Gravitational collapse
4
White Dwarf
5
Energy Output (Sun=1)
10 6
10 5
10 4
10 3
10 2
10 1
1
10 -1
10 -2
10 -3
10 -4
60,000
40,000
20,000
10,000
6,000
4,000
2,000
Surface Temperature (K)

# Edwin Hubble and the Discovery of Galaxies

## Lecture 31

**We've now reached the halfway point in this 60-lecture series. How appropriate, then, to start looking at the largest structures in the universe: galaxies, which are vast collections of stars.**

Stars do not occur in isolation. As we look into the sky with modest-sized telescopes we can see that the hazy band of the Milky Way is composed of countless millions of stars. Other objects that appear as fuzzy masses, too distant to resolve, were the subject of much debate in the early 20th century.

Some astronomers thought nebulae were nearby dust clouds, while others suggested they were more distant clusters of stars. As so often happens in science, improved instruments—in this case, more powerful telescopes—were the key to discovery. This issue was debated on April 26, 1920, at the American Academy of Sciences in Washington D.C. by Harlow Shapley (1885–1972) and Heber D. Curtis (1872–1942). Shapely felt that nebulas were nearby clouds of gases and dust; Curtis felt that they were much more distant clusters of stars.

The discovery of the nature of galaxies was made by American astronomer Edwin Hubble (1889–1953), a remarkable scientist who excelled as an athlete and a scholar. He won a Rhodes Scholarship to Oxford, where he studied law. Hubble then decided to change careers and went back to Chicago for a Ph.D. in astronomy. In 1919, he took a job with the Carnegie Institution of Washington at their new 100-inch telescope facility on Mount Wilson, near Los Angeles.

To resolve the nebula debate, Hubble focused on an unusual type of stars, called Cepheid variables, that get brighter and dimmer over a period of several days or weeks. The absolute brightness of these stars is directly related to the length of the cycle (discovered by Henrietta Swan Leavitt in 1912). By measuring the cycle and brightness of Cepheid variables, Hubble could tell their distance. Cepheid variable stars in the Milky Way ranged up to about

100,000 light years away. Cepheid variable stars in the galaxy known as the Andromeda nebula could be resolved for the first time at Mount Wilson, but they were extremely faint. M31 was thus estimated to be more than 500,000 light years away—far beyond the Milky Way. Hubble demonstrated that nebulae are vast, gravitationally bound collections of tens or hundreds of billions of stars. We call these objects galaxies.

**Galaxies are vast collections of gravitationally bound stars.**

Following Hubble's discovery, astronomers began an intensive search for galaxies—a search that continues today. Galaxies can be grouped into a few major categories. The most familiar are spiral galaxies, which account for about three-fourths of the brightest galaxies, including our own Milky Way. Spiral galaxies are characterized by beautiful arms that curve about a bright core. Seen on edge, spiral galaxies reveal a flat disk and central bulge.

Many other bright galaxies are more uniformly rounded collections of stars, without arms, called elliptical galaxies. Ellipticals represent about one-fifth of bright galaxies. They often contain hundreds of billions of stars. Smaller irregular and dwarf galaxies are relatively faint, but still remarkably abundant. A relatively small number of galaxies have chaotic shapes that result from the "collision" and gravitational linking of two former galaxies.

In describing galaxies, distance is one of the most important measurements. Much effort in modern astronomy is devoted to developing improved methods to determine these distances. Even the closest galaxies are much too far to use parallax. We must resort, instead, to objects of known brightness, called standard candles. This was the technique Hubble used when he studied Cepheid variable stars. That method, with improvements, is still used for galaxies up to a few tens of millions of light years. Other kinds of distinctive bright stars, including the brightest red giants and the brightest main sequence stars, called supergiants, also provide standard candles.

A special kind of exploding star, called a type I supernova, provides a much stronger standard candle for galaxies up to several hundred million light years away. Other approximate distance scales rely on the size and brightness

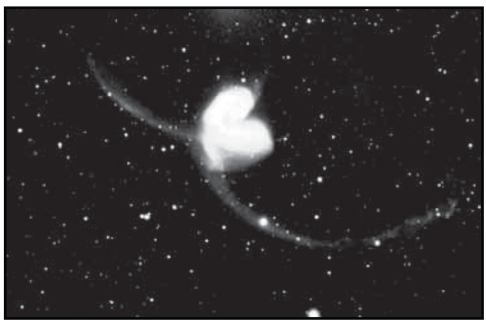
of entire galaxies. This procedure, which requires assumptions about the uniformity of galaxies across the universe, can take us to the very edge of the visible universe, billions of light years away.

Studies of standard candles led to yet another method for determining distances. Edwin Hubble used Cepheid variables to measure the distance to several nearby galaxies. Hubble and other astronomers also measured the relative velocity for these galaxies by their red shifts. The red shift is a change in the wavelength of light arriving from an object as a result of its relative velocity away from us. This is an example of the Doppler effect, which is most noticeable with the changing pitch of sound coming from a fast-moving object. The red shift is calibrated by characteristic emission lines from chemical elements.

Hubble discovered that more distant galaxies are moving away from us more quickly. Hubble's law states that velocity equals a constant (the Hubble constant) times distance:

$$v = H \times d$$

Thus, the red shift provides another cosmic distance scale for galaxies.



NASA.

**Irregular, dwarf galaxies are relatively faint but abundant.**

As telescopes have become more powerful, the number of known galaxies has grown tremendously. The Hubble Space Telescope recently focused on a very small area in an "empty" region of sky. This deep-field image showed dozens of faint, distant galaxies, never before seen. Red shift data indicate that some of these galaxies are many billions of light years away. Astronomers now estimate that there may be more then 50 billion galaxies, many with tens to hundreds of billions of stars.

A major effort is underway to map the distribution of galaxies in three dimensions. Galaxies themselves appear to be arranged in large-scale structures. Our Milky Way galaxy is part of the Local Group of about 30 galaxies, stretched out over a volume 3 million light years in maximum length. Several other clusters of galaxies are relatively nearby. The largest of these is the Virgo Cluster, which is 10 million light years across and has hundreds of galaxies. The Local Group, the Virgo Cluster, and several other clusters may be part of an even larger gravitationally bound Local Supercluster of galaxies, arranged in a disk more than 100 million light years across. The total mass of this collection is estimated to be about a million-billion Suns. Three-dimensional maps of huge numbers of galaxies are beginning to reveal amazing structures of galaxies in bands and along curved surfaces. Between superclusters are vast regions, called voids, with few galaxies.

One of the great mysteries in cosmology today is the origin of these gigantic structures, hundreds of millions of light years across. For answers, we may have to go back to the very beginning of the universe itself. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 15.

## Supplementary Reading

Christianson, *Edwin Hubble*.

Ferris, *Coming of Age in the Milky Way*.

Zeilik, *Astronomy*, Chapters 19–20.

## Questions to Consider

**1.** How would our galaxy appear from M31, the nearby Andromeda galaxy?

**2.** Philosophically, how did the discovery of billions of distant galaxies change our perceptions of our place in the Cosmos?

# The Big Bang

## Lecture 32

**Hubble's remarkable discovery of galactic red shift, that all the distant galaxies are speeding away from us, had remarkable implications for the origin of the universe. In fact, it now appears that the universe began at an instant of time approximately 14 billion years ago, and it has been expanding ever since.**

Hubble's discovery of the close relationship between a galaxy's distance and its velocity away from us immediately opened a new realm of scientific inquiry. Before those observations, any discussion of the origin of the universe was purely philosophical speculation. Hubble's reproducible observations pointed to an origin scenario that was both simple and testable.

But before examining evidence for the origin of the universe, we will review the scale of objects in the universe. The entire universe is approximately 30 orders of magnitude greater than the scale of everyday objects. Think about Hubble's discovery that distant galaxies are moving away from us; the farther away the galaxy, the faster its motion. Imagine playing a movie of this situation backward; all the galaxies would appear to converge to a point. Thus, at some point in the distant past, the universe appears to have begun at a point. The theory that the universe came into existence at one moment in time, and subsequently has undergone rapid expansion, is called the big bang.

What was the big bang like? It was not an explosion in which matter expands into an existing space. It was an expansion of space itself, along with all the matter and energy. The surface of an expanding balloon provides one helpful analogy. From a two-dimensional point of view, the balloon doesn't expand into anything—it just gets larger. Another analogy is provided by a large batch of raisin bread dough as it expands. From the point of view of any raisin, all other raisins are moving away. There is an assumption among astronomers of universal homogeneity; however, this hypothesis must be

accepted on an untested basis. In these analogies, the Earth does not occupy a special place. All observers see the same sort of expansion.

Three types of observation provide evidence to support the big bang theory.

- First are observations of the universal expansion of galaxies (cf., Hubble's findings in the early 20$^{th}$ century). However, expansion alone does not prove the big bang.

- Second is the universal background of microwave radiation that appears to pervade the universe. At the moment of the big bang, the universe was flooded with highly energetic electromagnetic radiation. As the universe expanded after the big bang, it began to cool, and the wavelengths of that radiation were stretched out to lower and lower energy. The background microwave radiation represents the remnants of that radiation. Researchers Arno Penzias and Robert Wilson of ATT Bell Labs discovered and P. J. E. Peebles of Princeton explained this phenomenon.

- Third, while almost all of the first atoms were hydrogen, a small amount of helium and lithium also appeared. Measurements of the relative amounts of these light elements provide evidence for the big bang.

If we postulate the big bang, we need to determine the age of the universe. We should be able to play the tape backwards, so to speak, to determine the starting point, and hence the age, of the universe. The age should be directly related to Hubble's constant, which tells us that if objects far away are receding slowly, then the universe is older; if they are receding quickly, then the universe is younger. But it is hard to make these measurements because of interstellar dust, which makes the relative light measurements hard to determine. Dust doesn't affect the red shift (thus we know how fast galaxies are moving), but it does make galaxies appear (optically) farther away than they really are.

Various teams of scientists have attacked this problem with differing results. Assuming no dust, the universe is about 20 billion years old. Assuming a

reasonable amount of dust, the figure is down to about 10 billion; however, there are individual stars estimated to be 11 or 12 billion years old. The best current estimate is older than 12 billion and younger than 16 billion years, with 14 billion being the current best guess as the figures are refined.

Measurements of the red shift of galaxies reveal additional surprises. Galaxies are gravitationally bound groups of stars, so they rotate about the massive central bulge. Seen on edge, one limb of a galaxy is rotating toward us and one limb away from us. Thus, the red shift varies slightly from one side to the other. In the 1970s, Carnegie Institution astronomer Vera Rubin was engaged in a methodical study of these galactic motions. After a few nights, a curious pattern emerged. She expected the rotation speed to drop off at the outskirts of a galaxy, where the mass was less concentrated. Instead, rotation speed was constant to the outermost reaches of the galaxy.

The problem of orbital dynamics requires a straightforward application of Newton's laws. All you need to know is the amount of mass and its distribution in space. The apparent mass of a galaxy can be estimated from the total number of visible stars, and the distances are known from standard candles. Rubin observed that galaxies appear to be rotating two to three times too fast for the known amount of mass in those galaxies. This situation became even more complex when astronomers began to use radio telescopes to map the atomic hydrogen that surrounds galaxies in a kind of halo. This halo extends far beyond the visible limits seen in optical telescopes and encompasses a volume that may be 10 times greater than the region of visible stars. The halo is also rotating much too fast. The only possible conclusion is that galaxies contain far more mass—typically 10 to 100 times more—than the visible stars would suggest. This discovery is called the missing mass, or the dark matter, problem.

What is dark matter? It does not seem to be ordinary dust or gas, because that much material would block out most light from a galaxy. One of the most obvious possibilities are a group of familiar objects called MACHOs—Massive Compact Halo Objects, such as planets, brown dwarfs, comets, and asteroids. However, all of these objects should emit heat radiation, yet infrared satellites don't detect anywhere near enough of these objects to make up 90% of a galaxy's mass.

Other possible sources of the missing mass require objects of a more hypothetical nature. If neutrinos have mass, for example, they'll add to the dark matter budget. Other astronomers invoke WIMPs—Weakly Interacting Massive Particles, or massive black holes. This is one of the exciting frontiers of science.

We have a strongly supported theory of how the universe began. Can we guess how it will end? Predicting the future requires playing our tape on fast forward. The ultimate fate will depend on a balance between the present expansion and the force of gravity, which must be slowing down that expansion rate. We can envision three possible scenarios. If the universe does not have enough mass, it will continue to expand forever, becoming more and more spread out, and growing gradually colder and colder. Such an ever-expanding universe is called an open universe. The universal expansion might gradually slow down but never quite stop in a flat universe. This result requires that the total mass in the universe exactly balance the expansion rate. If the universe contains more than a critical amount of mass, then the expansion will eventually slow down, stop, and reverse itself. The universe will ultimately collapse back onto itself in a "big crunch."

**The universe began at an instant of time approximately 14 billion years ago, and it has been expanding ever since.**

As we shall see in the next lecture, our understanding of the ultimate fate of the entire universe may ultimately depend on discoveries at the smallest imaginable scale of subatomic particles. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?*, Chapter 2.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 15.

## Supplementary Reading

Morris, *Cosmic Questions*.

Zeilik, *Astronomy*, Chapter 21.

## Questions to Consider

1. In what ways do the balloon and the raisin bread analogies reflect aspects of the expanding universe? In what ways are they misleading?

2. Why might scientists (or nonscientists, for that matter) have a philosophical preference among an open, flat, or closed universe?

# The Ultimate Structure of Matter

## Lecture 33

**I want to tell you about the structure of matter at its tiniest scale; this is a scale much smaller than the atom.**

One of the greatest challenges in physics is the search for a theory of everything, which is a single set of equations that describes the properties and behavior of all the different kinds of matter and forces in the universe. A theory of everything is an example of reductionism—the attempt to describe the physical universe in terms of its most basic building blocks. In the extreme, a reductionist might argue that all natural phenomena are predictable consequences of the behavior of the smallest particles and their interactions. The atomic theory was an early example of this philosophical approach, and some aspects of modern genetic research adopt this point of view as well. Some scientists argue that many collective properties of matter, notably consciousness, are not predictable from particles.

Much progress in devising a theory of everything is made by experimentalists, called particle physicists. As physicists probe smaller and smaller pieces of matter, they need higher and higher energies. The experimental hardware of these scientists are called particle accelerators. Theorists, who devise complex mathematical models of matter and forces, guide experimentalists.

Particle accelerators are machines that employ powerful electromagnetic fields to accelerate a beam of charged particles. Speeding particles collide, producing a shower of fragments, while detectors record the events.

The first high-energy physics experiments used cosmic rays—high-energy particles from space. In the 1930s, Berkeley physicist Ernest O. Lawrence invented the first particle accelerator, called a cyclotron. Subsequent machines, called synchrotrons and linear accelerators, may be several kilometers in length. As physicists search for more massive and ephemeral particles, they need larger machines. High energies are needed to make massive particles according to Einstein's equation, $E = mc^2$.

Gradually, as particle accelerators became more powerful, more elementary particles were discovered. At one point in the 1960s, there were hundreds of seemingly different particles, each with a characteristic mass, electric charge, spin, and other properties. Making sense of these particles was similar to the task that confronted Dmitri Mendeleev 100 years earlier. One key step was the recognition that some particles never reside in the atomic nucleus, while others appear always to be associated with nuclear processes in one way or another.

**Atoms are composed of even smaller particles, called quarks and leptons.**

Leptons, including electrons and neutrinos, are a class of six different particles that do not exist in the nucleus. Hadrons include all particles that can reside in an atom's nucleus, including the proton and neutron. The existence of hundreds of other hadrons suggested to many physicists that more fundamental particles might exist. Quarks, first proposed in the late 1960s by the American physicist Murray Gell-Mann, are a class of six different particles that combine in twos or threes to form hadrons. In addition to the 6 leptons and 6 quarks that comprise all matter, there are also antimatter particles. Antimatter particles, such as the positron, when combined with the corresponding matter, completely annihilate to energy. According to the current model, all the mass in the universe is made of 6 leptons, 6 quarks, and their 12 antiparticles.

One of the great mysteries of particle physics is the asymmetry of matter and antimatter in the universe. At the reductionist level, a complete description of the universe requires knowing all the types of matter and all the forces that cause matter to do interesting things. It appears that there are only four fundamental forces in the universe. Gravity is a relatively weak force that exists between any two masses, even over long distances. The electromagnetic force exists between any two electrically charged objects. It acts over long distances and is vastly stronger than gravity. The strong force operates only on the scale of the nucleus. It provides the binding energy for protons and neutrons in atoms. The weak force also operates only at the nuclear scale. It is responsible for the energetic release of an electron during beta decay.

According to the modern theory of particles and forces, called the standard model, the 12 fundamental particles of matter, the 12 antimatter particles, and all four forces are, at some deep level, one and the same. Imagine taking all of the familiar objects around you and placing them in an immensely hot fire, in which they all break down to a frenzied uniform mixture of protons and electrons. Only by cooling would we be able to "freeze out" the distinctive materials of our world. In the same way, physicists see the universe today as a place where different particles and forces have frozen out of an earlier, uniform, and perfectly symmetric time, when all the particles and forces were indistinguishable.

One way to imagine this situation is to think ourselves backward in time, to the big bang, when all the matter and energy of the universe appeared at a point. As the hot, compressed universe cools, a dramatic series of seven freezings take place. The earliest freezings involve separation of forces. The first occurred when the universe was only $10^{-43}$ seconds old. Gravity split off from the other forces, and universal expansion was opposed by gravity for the first time. At $10^{-35}$ seconds, the strong force froze out, so there were three seemingly different forces.

At $10^{-10}$ seconds, the weak force and electromagnetic force separated, so that all four forces we experience today had frozen out. Subsequent freezings led to the matter that we see today. Prior to $10^{-5}$ seconds, all particles were quarks and leptons (apparently with slightly more matter than antimatter). At $10^{-5}$ seconds, quarks combined to form hadrons. At 3 minutes, the first nuclei of protons and neutrons fused to form deuterium. These nuclei were surrounded by a sea of hot electrons, forming one immense plasma. At 500,000 years, the universe had cooled sufficiently that the first atoms formed, followed by gravitational clumping into stars, galaxies, and clusters of galaxies.

This standard model has nagging problems. The mathematical description of the standard model requires about a dozen separate "fundamental" constants, such as the mass of the electron and the speed of light. Each of these constants has to be determined separately. Many physicists feel that this aspect of the standard model lacks elegance. The force of gravity has not yet been successfully integrated into the standard model. The standard model does not yet fully explain dark matter.

What would it mean to discover a single set of equations that describes all types of matter and forces? Most people would agree with British astrophysicist Stephen Hawking, who argues that such a theory would be a major advance. Some scientists claim that such a discovery would mark the end of science: Everything of significance would then be known. Hawking pushes the hyperbole by calling a successful theory of everything the "ultimate triumph of human reason."

The American physicist Richard Feynmann saw a broader hierarchy of ideas. One extreme of this hierarchy encompasses overarching laws of physics, perhaps someday even a theory of everything. Moving up the hierarchy of ideas, one finds ever more complex concepts: the atom, heat, a salt crystal, a thunderstorm, frogs, an ecosystem, history, beauty. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?*, Chapter 3.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 2.

## Supplementary Reading

Hawking, *A Brief History of Time*.

Riordan, *The Hunting of the Quark*.

Trefil, *From Atoms to Quarks*.

## Questions to Consider

**1.** What is a reasonable number of fundamental particles, or fundamental constants?

**2.** Should a theory of everything be elegant?

# The Nebular Hypothesis

## Lecture 34

**I'm going to examine the hypothesis that all stars and planets form from the gravitational attraction of dust and gas in space; that's called the nebular hypothesis.**

The big bang filled the expanding universe with matter and energy. Almost immediately, gravity began to pull that matter into the clumps that would become stars, galaxies, and clusters of galaxies. Today, that star-forming process continues. Our galaxy features vast regions that are relatively rich in dust and gas. Exploding supernova stars add more raw materials for new stars. The shock wave from a supernova can trigger new star formation by creating locally dense regions in a dust cloud. In this lecture, we first review some of the objects that form our own solar system.

NASA and NSSDC.

**Saturn, one of the Jovian gas giants.**

The Solar System includes all objects that are gravitationally bound to the Sun. With telescopes we observe that nine planets, including Earth, orbit the Sun. The four inner planets—Mercury, Venus, Earth, and Mars—are called the terrestrial planets. They are relatively small, rocky worlds. The next four planets—Jupiter, Saturn, Uranus, and Neptune—are called the Jovian planets. They are gas giant planets, composed primarily of hydrogen. Pluto is an odd object. It is much smaller than the Jovian planets, and it appears to be rocky.

In addition to the planets, there are a number of other objects that are bound to the Sun, including planetary moons, asteroids, and comets. Comets may originate in the Oort cloud, which lies far beyond Pluto. The Kuiper Belt,

which also lies beyond Pluto, contains a large number of enigmatic objects in orbit. Astronomers have only recently begun to study these objects for clues about solar planetary formation.


Apollo 17 astronaut Harrison Schmitt standing next to a boulder in the Valley of Taurus-Littrow.

While most of our knowledge about the solar system comes from remote observations, scientists have occasionally been able to study samples from space. The vast majority of meteorites appear to be fragments of asteroids, but a small number bear strong evidence that they were blasted off the surface of Mars. Samples returned from the Moon, primarily by Apollo astronauts, have been instrumental in the development of new theories about the Moon's origin and evolution. Samples of interplanetary dust, recovered high in the Earth's atmosphere by U-2 aircraft, also provide insights into the life of our solar system.

Objects in the solar system display a number of distinctive characteristics. Most of the mass of the solar system is contained in the Sun, which is roughly 1,000 times more massive than all of the planets combined. Jupiter, the largest planet, is more than twice as massive as all other planets combined. All of the Jovian planets are much more massive than the terrestrial planets.

Even though the Sun is the most massive object in the solar system, more than 99% of the orbital kinetic energy of the solar system is in the Jovian planets. All planets orbit in almost exactly the same plane, which is defined in space by the 12 constellations of the Zodiac. All planets orbit in the same direction around the Sun. Looking down on the Northern Hemisphere of Earth, the orbits are counterclockwise.

We also learn about the Solar System's history from the age of its matter. Moon rocks display a variety of ages from almost 4.6 to about 3.2 billion years. Many meteorites also show a 4.6 billion year age.

The generally accepted model for the formation of stars, including the solar system, is called the nebular hypothesis. The theory was proposed by Pierre Simon Laplace (1749–1827), a French mathematician with a strong interest in physics and astronomy. According to the nebular hypothesis, gravity attracts dust and gas into an ever denser and more compact cloud. The composition of the nebula will be primarily hydrogen, with other elements depending on how many generations of supernovas contributed heavy elements to the cloud. The temperature of the collapsing cloud gradually increases as gravitational potential energy is converted to heat. The cloud probably starts off with irregular swirlings but, as the mass falls in toward the center, the cloud begins to rotate faster and faster, like a skater who pulls in her arms during a spin.

**Stars and planets form from the gravitational attraction of dust and gas in space.**

Eventually, the solar system looked like a rotating disk of matter with a large bulge at the center—not unlike a spiral galaxy. Most of the mass got pulled to the center; temperature and pressure inside the proto-Sun increased. At some critical point, nuclear fires inside the Sun ignited. A strong solar wind pushed outward from the Sun through the rest of the solar system. The heat and wind from our Sun stripped the inner planets of most of their hydrogen, helium, and other volatiles, leaving four rocky terrestrial planets. Much farther out, it was cool enough for hydrogen and helium to condense into the Jovian planets.

Many astronomers have wondered how likely it is to form a solar system like ours. One way of tackling this question is to devise computer models that keep track of the evolution of a dust cloud under gravity. Under most conditions, two stars will form a binary system. More than two-thirds of all nearby stars turn out to be part of binary systems. If Jupiter had been about 50 to 100 times larger, we would be in a binary system, too. When only one

star dominates a system, calculations show that a pattern of planets like our own is probable.

If solar systems form from contracting disks of gas and dust, then there must be many such objects in our own Milky Way galaxy today. The Hubble Space Telescope has produced a number of dramatic images of what are believed to be dynamic star-forming regions in nearby space. Hubble has also captured what appear to be stars surrounded by disks of dust. These may be solar systems in their first million years of formation.

Current models of the evolution of the Earth and Moon illustrate planet-forming processes. The moon is a real oddity. For example, it is the largest moon of any of the terrestrial planets. It is about the same age as the Earth, and its geologic properties are like those of the Earth's mantle. The Moon may have been produced by a collision with another planet in Earth's orbit, about 4.6 billion years ago. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 16.

## Supplementary Reading

Zeilik, *Astronomy*, Chapter 12.

## Questions to Consider

1. How might life on Earth be different if we lived in a double star system?

2. Does the Solar System have an "up" or "down" direction? Why do we adopt one orientation in preference to another?

# The Solar System

## Lecture 35

**I want to take you on a tour of the solar system. We're going to start nearest the Sun, with the swift, tiny planet Mercury, and work our way outward to the cold, dark, distant world of Uranus and Neptune.**

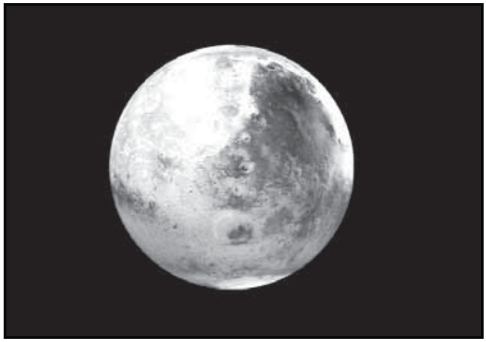
We live in a golden age of planetary exploration, when probes have visited every planet except Pluto. Spacecraft have landed on Mars and Venus and have penetrated Jupiter's dense atmosphere. Never before in history has the pace of planetary discovery been so rapid. In this lecture, we take a quick journey through the solar system. I will give the planets with mnemonic descriptions.

Mercury ("blasted and dead") is the innermost planet; it is a desolate and forbidding world. Its small size and proximity to the Sun have made Mercury extremely difficult to observe with Earth-based telescopes. Mercury's elliptical orbit takes it as close as 43 million kilometers and as far away as 70 million kilometers from the Sun. Its swift orbital period is just 88 days, while a "day" on Mercury lasts 176 Earth days.

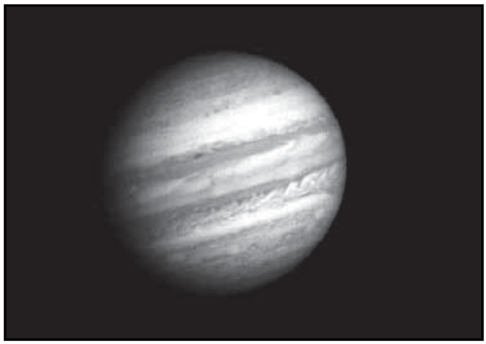
Our knowledge of the planet was greatly enhanced by Mariner 10, the only spacecraft so far to fly by Mercury. Photographs reveal a heavily cratered surface, alternately baked to 500°C by the Sun and frozen to −200°C on the dark side. Mercury has no atmosphere and thus no erosion to wear down the deeply pockmarked surface. Mercury's poles are in eternal twilight, since its axis has no tilt. It is possible that there is water at the poles.

Venus ("Earth-like with a greenhouse effect") is our nearest planetary neighbor, both in distance and in size. Its orbit is nearly circular, with an average distance of 108 million kilometers from the Sun and an orbital period of 225 days. Venus has a slow retrograde rotation about its axis, giving a leisurely "day" of 243 Earth days. The retrograde rotation is thought to be the result of a large impact near the end of the planet's accretion.

Venus is enshrouded in a thick atmosphere composed primarily of clouds of carbon dioxide and nitrogen. The daytime surface temperature reaches almost 500°C as a result of an exaggerated greenhouse effect. Surface pressure beneath the thick atmosphere is about 95 times that of Earth. Though the surface is forever hidden from view, the Venusian landscape has been mapped in detail by radar from the Pioneer Venus spacecraft.


NASA.

**Mars may once have held surface water.**


NASA.

**Jupiter is the largest by far of all the planets.**

The red planet Mars ("water and perhaps life") is by far the most intensively studied of our solar system neighbors because of the strong possibility that it once had abundant surface water. If any nearby planet harbors life, then Mars is the odds on favorite. Mars is about half the diameter and 11% of the mass of Earth. It has an elliptical orbit that averages about 1.5 times the Earth-Sun distance. The day on Mars is, coincidentally, close to 24 hours. Mars is tilted about 20° on its axis, so it has seasons like the Earth.

Mars has surface markings that are clearly visible from Earth. Most prominent are the polar ice caps, which wax and wane with the 686 day Martian year. The planet also shows brighter and darker reddish areas, with what appeared to 19th-century astronomers as linear features. Percival Lowell used the word "canals" to describe some of these features. Mariner spacecraft missions in the 1960s returned the first close-up pictures of the spectacular Martian surface.

Natural water-carved valleys, cratered plains, and huge volcanoes are seen. Viking lander missions of the 1970s returned pictures of a dry, barren, blasted world. The 1997 Mars Pathfinder mission featured both a lander and a six-wheeled, 23-pound rover named Sojourner.

Beyond Mars is the asteroid belt ("big rocks"), a broad band of rocky debris halfway to Jupiter just about where you might expect another terrestrial planet.

The character of the solar system changes radically beyond the asteroid belt, in the realm of the Jovian planets. Jupiter ("weather and amazing moons"), the largest of these giant planets, is a ball of hydrogen and helium about 2.5 times as massive as all the other planets combined. Jupiter is not massive enough to become a star. At five times the Earth-Sun distance, Jupiter orbits the Sun every 12 years. Day on Jupiter is only about 10 hours—a rotation so fast that the planet bulges about its middle. The rapid rotation also breaks Jupiter's thick atmosphere into fast-moving bands and swirls. The largest of these is the Great Red Spot. Much of our detailed knowledge of Jupiter has come from space probes, notably the Voyager spacecraft.

**The Earth and other planets are each unique worlds with unique characteristics.**

Astronomers have identified 16 moons of Jupiter, ranging from asteroid-like bodies less than 20 km in diameter to the planet-like Ganymede, more than 5,200 km in diameter. The four largest and most interesting moons are the Galilean moons—Io, Europa, Ganymede, and Callisto—discovered by Galileo Galilei with his telescope in 1609. Each of these moons is a distinctive world of its own, in many respects more like a terrestrial planet. Europa is the smallest of the Galilean moons, but by far the most interesting. Its surface is covered by what appears to be a cracked ice sheet that may cover a thick water ocean. If tidal stresses keep this ocean warm, then Europa may harbor the most Earth-like environment elsewhere in the solar system. The space probe Voyager also found other smaller moons and rings.

Saturn ("rings and Titan"), the second largest planet, has breathtaking rings. Saturn is similar in composition and character to Jupiter, though only a third

the mass. Saturn is almost ten times farther from the Sun than Earth, and it takes almost 30 years to complete one orbit. Its 10-hour day, like Jupiter's, causes an equatorial bulge and severe weather. It, too, is predominantly hydrogen (73%) and helium (26%), with colorful carbon-based compounds in the violently churning atmosphere. The magnificent ring is actually a complex system of ringlets that appear in detail like grooves on a record.

Astronomers have identified about 20 moons that are greater than 15 km in diameter. While most of these are irregular, asteroid-like bodies, the largest moon, Titan, is a uniquely fascinating world. Titan is the largest moon in the solar system, even larger than our own. Titan is larger than Mercury, though only half as massive owing to its composition that is about 50:50 ice and rock. Titan has a substantial nitrogen atmosphere, with a surface pressure about 1.5 atmospheres. It is quite cold.

The outermost planets are not visible to the unaided eye. Uranus ("gas giant and Herschel family") was discovered in 1781 by the English astronomer William Herschel (1738–1822). Uranus is about 19 times the Earth-Sun distance, with an orbital period of 84 years. The planet is more than four times the diameter of Earth and 100 times more massive. Voyager 2 revealed that the Uranian day is about 17 hours and that the rotation axis of Uranus is on its side relative to the other planets. Thus, unlike other planets, each pole of Uranus receives direct sunlight for 42 years at a time. Like the other gas giants, it is composed mainly of hydrogen and helium.

The discovery of Neptune ("gas giant and blue") was a triumph of the Newtonian model, since its existence and approximate location were deduced from perturbations in the orbit of Uranus. The planet was discovered by French astronomers in 1846. Neptune is 30 times the Earth-Sun distance, with an orbital period of about 165 years. It takes light about four hours to travel from the Sun to Neptune. Most of our knowledge of the planet comes from the Voyager 2 flyby in 1989, which photographed the beautiful blue planet.

The physical and chemical characteristics of these other planets may hold the key to understanding our own dynamic world. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 16.

## Supplementary Reading

Greeley, *Planetary Landscapes*.

Hartmann, *Moons and Planets*.

Zeilik, *Astronomy*, Chapters 9–11.

## Questions to Consider

1. Summarize the role that unmanned spacecraft have played in the exploration of the solar system. Check out NASA web pages to find out what other planetary missions are being planned.

2. What priority should be placed on human exploration of other planets and moons?

# The Earth as a Planet

## Lecture 36

**Our home, planet Earth, is one of nine—or perhaps only eight—planets that orbit the Sun. They were formed 4.5 billion years ago in a solar nebula.**

In this lecture, we first complete our travelogue through the Solar System. Pluto, the ninth planet, is an enigma. The existence of a ninth planet was suspected from slight perturbations in Neptune's orbit. It was discovered by American astronomer Clyde Tombaugh in 1930. Pluto is unlike the other planets in several respects. It is quite small, with a radius of 1,140 km, or about two-thirds the size of the Moon. It is half rock and half ice. Its extremely elliptical orbit occasionally brings Pluto closer to the Sun than Neptune. Pluto's orbit is also significantly tilted to the plane of the other planets. These characteristics have led some astronomers to suggest that Pluto is an escaped moon of Neptune. Pluto is, in effect, a double planet. Its moon Charon is about half its size and in a close orbit.

Out beyond Pluto are still more solar system objects. The Kuiper Belt contains numerous objects up to a few hundred kilometers in diameter. From their darkness, they appear to be at least partly rocky. There are two basic groups of Kuiper Belt objects, termed "blue" and "red" based on the light reflecting off them. Some scientists have proposed that Pluto is the largest of the Kuiper Belt objects.

NASA.

Halley's Comet, the first comet whose orbit was predicted.

Comets, the most distant known objects that are gravitationally tied to the Sun, have extremely elliptical orbits with an average distance about 50,000 times the Earth-Sun separation, or about three-

fourth of a light year. The Dutch physicist Jan Oort proposed that comets originate in an area now called the Oort cloud. There are several well-known ancient and more recent comets, e.g., Halley's Comet, Shoemaker-Levy, Hale-Bopp, and others.

Before turning to Earth, consider one other hot area of planetary research—the search for extrasolar planets. Powerful telescopes provide opportunities for the first time to detect the presence of planets orbiting nearby stars, less than 100 light years away, by noting the "wobble" of stars. More than a dozen planets the size of Jupiter or larger have been detected in this way, and more are being found every month. Planned interferometric space telescopes bring us new knowledge about these intersolar planets.

The Earth is like the other planets of the solar system in many respects. It orbits in the same plane and in the same direction; it formed at the same time; it is composed of the same chemical elements and obeys the same physical laws. But the Earth is also unique in that it has extensive surface deposits of liquid water—the essential medium for life as we know it. Many of the characteristics of Earth seem well suited to a habitable surface.

**The Earth, formed by gravitational attraction of dust and gas, differentiated into the crust, mantle, and core.**

Earth is about 150,000,000 km from the Sun—close enough to maintain liquid water, but not so close as to boil it away. The 24-hour rotation period is short enough to prevent extreme temperature contrasts between night and day, but slow enough to prevent extremely violent weather patterns. The Earth, with a radius of 7,000 km, is large enough so that fast-moving water molecules cannot escape the planet, as they do on Mars.

The Earth formed during a time called the great bombardment. In the final stages of accretion, the surface of the Earth was a hellish place of molten rock, spewing out gases and constantly blasted by the incessant rain of comets and asteroids. As the bombardment subsided, the red-hot molten sphere slowly cooled and a black rocky crust formed. The intense volcanic

activity pumped nitrogen, carbon dioxide, water, and other gases into the young atmosphere. Eventually, as the surface cooled in places to below the boiling point of water, torrential rains flooded the land and ocean basins began to fill. Late-stage large impacts, including the one that formed the Moon, would have blasted away any oceans and atmosphere. These would have had to form all over again.

Deep inside the molten primitive Earth, different kinds of material began to separate by the process of differentiation. This process has given the Earth a radially layered structure, not unlike an onion. The densest material, primarily iron and nickel metal, sank to the center of the growing planet. Ultimately, this iron metal core increased in size to a sphere about 3,470 km in radius. Much of the lightest material concentrated near the surface to form a relatively thin crust, typically less than a few tens of kilometers. The remaining material—about 80% of the volume and two-thirds of the mass—form the Earth's mantle, which is composed primarily of the elements oxygen, silicon, magnesium, and iron.

Seismology, the study of the Earth's inner structure using sound waves, provides our clearest picture of the Earth's deep interior. Sounds waves pass through the Earth at speeds typically a few kilometers per second. The speed increases through denser or colder material, and it decreases through material that is less dense or hotter. Seismic waves bend as material changes density with depth. Waves are partially reflected off abrupt changes in material, like the core-mantle boundary. There are compressional primary waves, or p-waves, and shear secondary waves, or s-waves, defined by the orientation of their basic movements. These waves have different transmission characteristics. Most seismic waves are generated by earthquakes, which are sudden movements of rock, usually in the crust or upper mantle.

Seismology reveals details of the Earth's deep interior. The core is divided into a solid inner core, with a radius of 1,200 kilometers, and a liquid outer core. The Earth's mantle is divided into three major layers, each bounded by seismic discontinuities, and each with different minerals.

Seismology, coupled with geological field studies and deep drilling, reveals that the Earth's crust is an extremely heterogeneous place, with complex structures that point to a dynamic history. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 17.

## Supplementary Reading

Boss, *Searching for Earths*.

Press and Siever, *Understanding Earth*, Chapters 1 and 19.

Zeilik, *Astronomy*, Chapters 11–12.

## Questions to Consider

1. All models of star formation also lead to the formation of planets. Why, then, should observations of extrasolar planets be considered exciting discoveries?

2. Is there any reason to suspect that Earth-like planets exist in other star systems?

*Note*: Customers interested in an even more detailed investigation of the cosmos might want to consider acquiring the course *Understanding the Universe: An Introduction to Astronomy, 2nd Edition* by Dr. Alexander Filippenko of the University of California, Berkeley.

The course *Einstein's Relativity and the Quantum Revolution: Modern Physics for Non-Scientists, 2nd Edition,* by Dr. Richard Wolfson of Middlebury College, provides an excellent introduction to theories of space, time, light, and energy and discusses in some detail the actions of sub-atomic particles and cosmic evolution, thus complementing this course by Dr. Hazen.

# The Joy of Science (Lectures 37–48)

**Scope:**

The next part of this lecture series focuses on great principles related to planet Earth and its most complex systems—life. Studies of Earth and life differ from physics and chemistry in that they deal with extremely complex systems that have a distinctive and contingent history. The present state of a rock or a tree depends on an intricate and irreversible past. Engaging in geological or biological research, therefore, is often akin to detective work, where clues are precious, and imagination plays a vital role.

Geological studies of the Earth's surface reveal billions of years of geologic change (Lecture 37). The global process of plate tectonics links the convection of soft, hot rocks in Earth's deep interior to motions of thin, brittle tectonic plates near the surface (Lectures 38 and 39). All the materials of the Earth, including water, air, and rock, are constantly recycled (Lectures 40–42).

All life on Earth has the ability to obtain matter and energy from its environment, to grow, and to reproduce with variations. All living things must adopt strategies to compete for resources and survive variations in the environment (Lectures 43 and 44). All living things are made from versatile carbon-based molecules, including lipids, which form cell membranes, and carbohydrates, which provide structures for plants and energy-rich molecules for all living things (Lecture 45). Proteins are the chemical workhorses of life; built from chains of amino acids, their structure determines their function (Lecture 46). All living things are made of one or more cells, which control the synthesis of these molecules and other chemical reactions essential to life (Lecture 47). All life must also pass information from parent to offspring by genetic processes that were first quantified by the Czechoslovakian monk Gregor Mendel (Lecture 48). ■

# The Dynamic Earth

## Lecture 37

**I'm going to begin by telling you about two of the most violent and destructive events that can occur on Earth's surface; that is, earthquakes and volcanoes. But geological change isn't always violent. It can also occur through gradual change, through processes like erosion, and sedimentation, and uplift; and we'll look to see how those processes can lead to dramatic change as well.**

Our planet Earth is one of the most active and dynamic bodies in the solar system. On the scale of human lifetimes, the Earth's major features—mountains and valleys, rivers and deserts, continents and oceans—seem permanent and unchanging. But a closer look will convince you that the solid Earth is a planet characterized by constant change. Some agents of change are violent and sudden, such as earthquakes and volcanoes, while other natural processes achieve change gradually.

An earthquake is a shaking or vibration of the ground, caused by a sudden slip along a break, or fault, in the Earth. It results from the gradual buildup of stress between two blocks of rock. Suddenly, the blocks slide past each other—sometimes by as much as several meters—releasing huge amounts of energy. Because of this mechanism, earthquakes are extremely difficult to predict.


U.S. Geological Survey, Harry Glicken, USGS/CVO.

Mount Saint Helens, an active volcano.

Earthquakes are measured according to how much energy is released, which is often closely related to how much damage is caused. Each time an earthquake occurs, two blocks of rock move a short distance along a fault, but these

motions aren't random. The same fault slips over and over again, often accumulating hundreds of kilometers of relative motion.

Unlike an earthquake, a volcano is a mountain or other feature that forms when molten rock erupts as lava and accumulates at the surface. Volcanoes require a plumbing system that conveys a reservoir of molten rock, or magma, to the surface. Prior to an eruption, the reservoir will gradually fill with magma as hot as 1,200°C. Hundreds of millions of people live in the shadow of great volcanoes. Volcanoes in Hawaii and Iceland produce predictable lava flows that may swallow up houses but which rarely claim lives. Far more dangerous are volcanoes that build up internal pressure and suddenly burst.

**The surface of the Earth reveals billions of years of geologic change.**

Volcanic eruptions are easier than earthquakes to predict because monitors can sense the buildup of magma months before a major eruption. Volcanoes, though seemingly remote and unusual phenomena, have shaped much of the planet. About 80% of the Earth's surface, including virtually all of the ocean floors, is covered by volcanic rock.

The doctrine that geological changes take place over millions of years of gradual increments is called uniformitarianism. The founder and first champion of uniformitarianism was Scottish geologist James Hutton (1726–1797). At that time, the prevailing wisdom was that the Earth was about 6,000 years old, in accordance with the literal interpretation of the biblical chronology proposed by Irish Bishop James Usher (1581–1656). Most geological features were interpreted as the result of one great catastrophic flood. This belief supported two prevailing geological doctrines of the 18th century—catastrophism (that geological changes occur primarily through the action of catastrophes), and neptunism (that rocks are formed primarily through the action of water).

Hutton realized that the most dramatic changes in the Earth's surface are told by the testimony of the rocks in outcroppings and cliffs. His interpretation of a remarkable cliff near the town of Jedburgh, Scotland, epitomizes his

thinking. In these rocks Hutton saw a succession of periods of sedimentation, burial, compression, folding, uplift, and erosion. These processes are gradual and uniform, as opposed to the views of the catastrophists. He also saw the Earth's inner heat as an essential agent of change—a point of view called volcanism, in contrast to neptunism.

Hutton's ideas were published in his revolutionary, but unreadable, *Theory of the Earth* (1785). Hutton said rocks reveal: "No vestige of a beginning, no prospect of an end." Hutton's friend, John Playfair, aided the acceptance of uniformitarianism by his persuasive popular account, *Illustrations of the Huttonian Theory of the Earth* (1802).

Many other examples of the dramatic consequences of slow, cumulative change can be seen around the world. The existence of tall mountains, for example, is evidence that large-scale geological processes must still be operating on Earth today. The processes by which mountains form, called tectonics, is the subject of the next lecture. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 17.

## Supplementary Reading

Press and Siever, *Understanding Earth*, Chapters 5, 15–18.

## Questions to Consider

**1.** If a major earthquake along the San Andreas Fault could be predicted to within one month, what should authorities do with that information? Would your answer be different if a major quake could be predicted within three days?

**2.** No building codes can protect citizens from a pyroclastic volcanic flow. What regulations, if any, should Washington State place on residents down slope from Mount Rainier?

# The Plate Tectonics Revolution

## Lecture 38

**Scientific revolutions are few and far between, but those of us who have been lucky enough to be Earth scientists in the last 30 or 40 years have seen just such a transformation: a transformation in the earth sciences called the plate tectonics theory.**

The theory of plate tectonics caused a revolution in the discipline of earth sciences. This revolution took place swiftly and rather quietly, and the history of the theory and its acceptance reveals much about the nature of the scientific process.

When I was an undergraduate in the late 1960s, every textbook and every introductory geology course proclaimed that the Earth's oceans and continents were more or less permanent features of the globe. Mountain building was thought to be a vertical process. Mountains were thought to be great rafts of relatively light material buoyed up like an iceberg on the ocean. The term for this concept is isostacy. Geological processes were thought to be local and idiosyncratic. Earth sciences were similarly fragmented into subdisciplines.

The theory of plate tectonics was preceded by the curious hypothesis of continental drift, which was proposed by the German meteorologist Alfred Wegener (1880–1930) in 1912. Wegener's theory of continental drift was predicated on several intriguing observations regarding match-ups of geological features across the Atlantic Ocean. The principal objection to Wegener's hypothesis was that it lacked a mechanism for moving entire continents.

The plate tectonics revolution resulted primarily from the merging of six separate lines of observational evidence. The oldest observational evidence for moving continents is the parallel shape of Africa and Europe compared to North and South America.

Second came Wegner's analysis. Much of Wegener's geological evidence was sound and intriguing. Major deposits of rocks, minerals, and fossils seem

to match up exactly across the Atlantic, like pieces of a jigsaw puzzle. For example, Brazil and South Africa both feature large and distinctive regions of ancient diamond-bearing sediments. Rare and distinctive fossils come from the southern coast of Wales and near Boston, Massachusetts.

The non-uniform distribution of earthquakes and volcanoes provided a third body of evidence for plate tectonics. Most earthquakes and volcanoes occur in narrow bands around the globe (e.g., the Ring of Fire, which runs along the rim of the Pacific Ocean). As more seismic stations were established, these patterns were refined.

A key piece of the puzzle came shortly after World War II, when the Navy declassified sonar technology used to track enemy submarines. Sonar was easily modified to measure the topography of the sea floor. Conventional wisdom in the 1950s was that the ocean floor was as flat and featureless as anywhere on Earth. The first sonar traverses of the Atlantic Ocean revealed the Mid-Atlantic Ridge, the longest mountain chain on Earth, which runs the full length of the North and South Atlantic, almost exactly halfway between the continents and roughly parallel to the curving coastlines.

The discovery of the Mid-Atlantic Ridge, and its subsequent widespread recognition, was due in large measure to the American geologist Bruce Heezen (1924–1977). Following Heezen's work, Princeton geologist Harry Hess (1906–1969) contributed a seminal paper that described the mid-ocean ridges as places where new ocean crust is formed and spread laterally—a mechanism that could explain the opening of the Atlantic Ocean.

The ages of volcanic islands in the Atlantic Ocean provide yet another clue. Radiometric techniques were used by geologists to date rocks from islands such as Iceland and the Falklands. In 1964, a Canadian-born geologist working at Princeton University, John Tuzo Wilson (1908–1993), found a striking trend. Islands that lie close to the Mid-Atlantic Ridge are relatively young, whereas islands far off the ridge are much older.

The most convincing evidence for the formation of new crust at ridges came from sea-floor magnetic data. Ocean magnetometers, again developed by the Navy to find submarines, were declassified in the 1950s and were

used to measure the magnetic orientation of rocks on the ocean floor. When volcanic rocks cool, they freeze in the orientation of the Earth's magnetic field. As ships sailed across the ridges, the magnetic orientation kept flipping back and forth by 180°. These observations provided compelling evidence that the Earth's magnetic field reverses. The fact that the magnetic stripes were parallel and symmetric about the ridge line was strong evidence for an expanding ocean. This finding was announced in a seminal article by Drummond Matthews and Frederick Vine in the September 7, 1963 issue of *Nature* magazine. A perhaps even more influential article by Vine and Wilson appeared in *Science* in 1965.

The acceptance of plate tectonics theory was swift and overwhelming; the few key remaining problems were quickly solved. Earth's surface is broken into about a dozen tectonic plates, which are relatively thin, brittle slabs of rock no more than a few tens of kilometers thick but up to thousands of kilometers across. Movement of tectonic plates occurs at three types of plate boundaries. The Mid-Atlantic Ridge is an example of a divergent boundary, where new crust is formed. This crust moves away from both sides of the Ridge, like material on a broad conveyor belt. Thus, magnetic strips are parallel and symmetric about the Ridge, and volcanic islands farther from the ridge are older. Old crust is taken back into the mantle at convergent boundaries. This process occurs in those areas around the Pacific rim where earthquakes and volcanoes occur in proximity. A third type of plate contact, called a transform boundary, occurs where two plates slide against each other. The San Andreas Fault is an extensive transform boundary that divides California at the junction of the North American Plate and the Pacific Plate.

**Convection of soft, hot rocks in Earth's deep interior causes thin, brittle plates of rock to move at the surface.**

A second key question was the source of energy that powers the movement of entire continents. Geophysicists quickly realized that the only energy source large enough to generate such a force is the Earth's own internal heat. At the elevated temperature and pressure of the deep interior, many rocks become relatively soft and plastic. Plate motions are driven by the convection of hot, plastic rock in the Earth's mantle. The

development of this convincing underlying mechanism for plate movements ensured the almost universal acceptance of plate tectonics.

The theory of plate tectonics had tremendous power and appeal. The theory successfully synthesized new data from many subdisciplines: oceanography, paleontology, petrology, geomagnetism, and so forth. The theory thus integrated the earth sciences as never before. It provided new ways to analyze old, puzzling geological data about the evolution of continents and oceans and the life forms they supported. Plate tectonics theory made specific, testable predictions about the dynamic Earth. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 17.

## Supplementary Reading

Press and Siever, *Understanding Earth*, 2nd edition, Chapter 20.

Wood, *The Dark Side of the Earth*.

## Questions to Consider

**1.** How does the development of the theory of continental drift illustrate the scientific method in action?

**2.** What does the development of plate tectonics reveal about the role of new instruments in science?

# Earthquakes, Volcanoes, and Plate Motions Today

## Lecture 39

**After reviewing the evidence for plate tectonics, I'll examine the nature of the Earth's tectonic plates and their three different kinds of dynamic boundaries. These are, first, the divergent boundaries, at which new crust is formed; the convergent boundaries, where old crust is swallowed up; and finally, transform boundaries, where two plates scrape by each other.**

In science, simple theories that explain a wide variety of observations in a single unifying framework are most valued. Plate tectonics is such a grand theory. It ties together data on minerals and fossils, earthquakes and volcanoes, surface geology and the structure of the deep interior. Plate tectonics is crucial to understanding long-term variations in climate, the distribution of ore deposits, and pathways of life's evolution. This lecture examines plate tectonics and its consequences in more detail.

Rocks near the Earth's surface can be described in terms of their rigidity. The lithosphere, including the crust and the top part of the mantle, is relatively thin, cold, and brittle. This strong rock layer is typically between 50 and 100 km thick. The lithosphere rides on the relatively soft, hot asthenosphere, which extends deep into the mantle.

**Most earthquakes and volcanoes arise from dynamic processes associated with plate motions.**

Tectonic plates are wide pieces of lithosphere that are shunted about by convective movements of the asthenosphere. In this scheme, continents are like giant rafts of relatively light rocks and minerals that float on top of the lithosphere. A map of the world's plates shows about a dozen large, rigid plates distributed across the globe. The map of plate boundaries also reveals relative plate motions at divergent, convergent, and transform boundaries.

Divergent boundaries mark elongated zones along which new crust is formed. Two plates diverge above a region where mantle convection brings heat to the surface. The excess heat causes partial melting of the near-surface rocks. This magma supplies volcanoes along the spreading axis. The lava produced at ridge volcanoes is typically basalt, a dense, black rock rich in oxides of silicon, magnesium, and iron.

The Earth's surface features many prominent divergent boundaries. The Mid-Atlantic Ridge, which extends for tens of thousands of kilometers, is now spreading at 2–4 cm per year. Playing the tape backward, at current rates of spreading, the Atlantic began to open up about 200 million years ago. The East Pacific Rise is a major divergent boundary in the South Pacific Ocean. Spreading rates as high as 17 cm per year have been measured. All of the oceanic ridge systems display complex hydrothermal systems, where sea water filters deep underground through cracks and is heated by the volcanic activity. Mineral-rich "black smokers" that support astonishing deep-water ecosystems have been found along all the major ridges.

Convergent boundaries mark zones where the relative motion of two plates is toward each other—a situation that arises above zones of down-welling mantle convection. Boundary details depend on whether one or both of the converging plates carries continental material. If neither plate carries continental material, then one oceanic plate plunges beneath the other—a process called subduction. If only one plate carries continental material, then the other plate invariably subducts beneath the continent. Cold plates are dense relative to the hot mantle, so gravity helps pull plates into the mantle. Rates of subduction are comparable to rates of divergence—a few centimeters per year.

Subduction zones are sites of intense geological activity. The process of subduction is accompanied by numerous deep earthquakes that concentrate inland of the subduction zone. Subduction zones are also associated with intense volcanism. Wet subducting rocks partially melt, forming magma that works its way back toward the surface. Because of the slope of subduction, the resulting volcanoes occur 100–200 km away from the deep ocean trench. Island arcs and inland volcanoes are a consequence of subduction. Reworking of crust by subduction also can lead to the solution and concentration of

valuable ores. Many of the world's richest metal deposits are associated with ancient volcanoes that formed near convergent boundaries.

Occasionally, two converging plates both carry continental material. Because continental rocks are relatively light, they will not be subducted into the mantle. Today, such a collision is happening at the boundary between the Eurasian and Indian Plates, the location of the world's tallest mountain range, the Himalayas. A similar collision took place about 400–500 million years ago to form what became the Appalachian Mountains.

Transform boundaries are faults where two plates slide past each other. Such boundaries are inevitable on a sphere with divergent and convergent boundaries. The San Andreas Fault is the longest highly active transform boundary. Major earthquakes occur along this fault every few decades. All of the Earth's ocean ridge systems are offset, sometimes by several hundred kilometers, by dozens of small transform faults. Dormant boundaries (e.g., those between Africa and Asia) are another type of transform boundaries.

Mantle convection drives plate tectonics and controls the location of most of the Earth's volcanoes. Yet some well-known volcanic areas, including Hawaii and Yellowstone, are in the middle of a plate. A different kind of mantle convection, as yet poorly understood, produces these volcanic hot spots. Hot spots arise when a narrow plume of magma rises from deep within the mantle, perhaps from the core-mantle boundary almost 3,000 km down. The location of hot spots seems to be independent of plate tectonic processes. As the Pacific Plate moves over the fixed Hawaiian hot spot, new islands are formed. About 30 other hot spots are recognized around the world. A more complete understanding of their origins remains a hot topic of research. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 17.

## Supplementary Reading

McPhee, *Annals of the Former World*.

Press and Siever, *Understanding Earth*, Chapters 1 and 20.

## Questions to Consider

**1.** Where is the nearest plate boundary to your home? Are there any geological hazards associated with that boundary?

**2.** Strong earthquakes occasionally hit areas deep in the middle of tectonic plates. Boston, St. Louis, and Charleston, for example, have all experienced damaging shocks in the past 250 years. From what you know about the rigidity of plates, how could such earthquakes occur?

# Earth Cycles—Water

## Lecture 40

**The Earth is a magnificent physical system. It's a great collection of atoms that are constantly changing, constantly reorganizing themselves, as the globe itself undergoes change. [This] is the first of three lectures on the great geochemical cycles of the Earth: the cycles of earth, air, and water.**

Every type of material we use in our lives comes from the Earth. Every element and chemical compound can be described in terms of a geochemical cycle. A geochemical cycle involves two types of information. First is a list of all reservoirs of that element or compound. Second is a list of the processes by which substances move from one reservoir to another.

The geochemical cycle of the element gold provides an example. Major known gold reservoirs include the oceans (about 50 $kg/km^3$), hydrothermal fluids, metal ore bodies, rocks and soils, and bank vaults. Gold atoms are moved by water, which dissolves rocks and soils. Humans have extracted large amounts of gold from ore bodies and placed it in vaults and in jewelry.

There are hundreds of individual geochemical cycles to study, but, three major Earth cycles are of primary concern: the water cycle, the atmospheric cycle, and the rock cycle. Though different in detail, these cycles share four characteristics. All of these cycles involve the movement of matter among reservoirs. All of these cycles are driven by energy from the Earth and the Sun. All of these cycles can be altered by human activities. All of these cycles are interrelated.

Water plays a unique role in the geological and biological history of the Earth's near-surface environment. The Earth's water budget is almost completely closed. There are six major repositories of accessible water on Earth. These reservoirs include the oceans, ice caps and glaciers, fresh water lakes and rivers, groundwater, the atmosphere, and living organisms. Hydrous minerals, which incorporate water molecules, $H^+$, or $OH^-$ groups

into their crystal structures are a potentially vast, but relatively inaccessible, reservoir of water. The mantle may hold many times the total accessible water of the surface. This water, furthermore, slowly recycles to the surface through ocean ridge volcanism.

Oceans are by far the largest accessible reservoir of water. They now hold almost 98% of all accessible water. Oceans cover about three-fourths of the Earth's surface to an average depth of about 2 km. Water is an excellent solvent of ionically bonded salts. Over billions of years of geological time, the oceans have thus become salty.

Glaciers and ice sheets now contain an estimated 2% of Earth's accessible water. Most of this ice covers the land masses of Antarctica and Greenland. The rest occurs as thin coverings of the polar oceans and widely scattered mountain glaciers at high altitudes. The distribution of water between oceans and ice reservoirs can change dramatically, with profound effects on the world's ecosystems.

**The Earth's store of water is essentially unchanging; the same molecules are recycled over and over again.**

Fresh water on land accounts for, at most, about 0.4% of all accessible water. Of this amount, more than 90% is stored beneath the surface as groundwater. Huge underground reservoirs are formed by porous rock layers that are sandwiched between impervious layers. Lakes, rivers, and streams, though a major source of water for humans, represent less than 0.04% of the Earth's near-surface water. The atmosphere holds perhaps 0.001% of Earth's water, mostly in clouds.

Part of the reason that Earth is such a dynamic planet is that water constantly moves from one reservoir to another. Parts of this cycle are experienced on a daily time scale. The hydrological cycle features complex and interconnected movements of matter. The principal movement of water out of the oceans is through surface evaporation into the atmosphere. Ocean waters are layered; deeper layers are generally colder, saltier, and denser. Only the surface waters participate in evaporation. Ocean surface currents move warm water

from near the Equator to higher latitudes. There the water cools and sinks, forming deep, cold currents that flow back toward the Equator. In this way the oceans play a major role in distributing heat across the globe.

Fresh water is transferred from atmosphere to the surface primarily by rain and snow. The average residence time for a water molecule in the atmosphere is only a few days. Most rain falls back onto the ocean. Rain replenishes lakes and rivers quickly, but rainfall may take hundreds to thousands of years to reach a groundwater reservoir. The system of streams and rivers continuously returns fresh water back to the oceans.

Ice caps and glaciers also participate in the water cycle. Snowfall adds to the net budget of ice and snow, while melting, sublimation, and breakup of ice sheets subtracts. While these processes are generally slow on human time scales, major changes in the proportions of oceans and ice have occurred often in geological history.

Ice ages represent a part of the water cycle that spans millions of years. An ice age is a period of geological history when a relatively high percent of the Earth's surface water becomes locked into ice caps and glaciers. The Earth's present ice caps began forming about 10 million years ago; for a long time prior to that, there were no permanent ice caps. Many times during the past 2 million years the northern polar ice sheet has expanded south to cover much of North America and Europe and then retreated, in a cyclical pattern. During the most recent glacial advance, about 20,000 years ago, sea level was hundreds of meters lower than today. The East Coast of North America was 250 kilometers farther east, and a land bridge connected Alaska and Siberia across what is now the Bering Sea. At the height of these periodic glacial advances, as much as 5% of Earth's water became locked in ice.

Plate motions probably explain the formation of ice caps 10 million years ago. Thick ice caps can only form when a continent is at or near one of the poles. We are now in a relatively unusual period when the Antarctic continent occupies the southern pole, and large portions of Eurasia and North America lie inside the Arctic Circle. An explanation for the periodic advance and retreat of glaciers during the present ice age was suggested by

the Serbian civil engineer Milutin Milankovitch. Milankovitch explained periodic glacial advance and retreat as a result of orbital variations, which cause a slight shift in the amount of solar radiation reaching the Northern and Southern Hemispheres.

Living things, including humans, require water to survive. Thus, while organisms hold a trivial fraction of all near-surface water, all life forms must develop a strategy to obtain a reliable water supply. A human being requires about 2 liters of water per day, but the per capita consumption in an advanced industrial society is about 6,000 liters per day. We use several hundred liters per day in personal activities. Most of the per capita usage is the result of irrigation for agriculture and industrial processes.

As human population grows, we are faced with important problems related to water use. First and foremost is the problem of water pollution. All water contains impurities because water is such an excellent solvent. Buried chemical waste, old batteries, and trash all react with groundwater. Rivers and lakes can be cleaned up relatively successfully, but today's pollution may affect groundwater reservoirs for long periods. A more immediate problem with groundwater reservoirs is overuse. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 18.

## Supplementary Reading

Skinner and Porter, *The Blue Planet*, Chapters 8–10.

## Questions to Consider

1. Based on how we obtain water for irrigation in the United States, should we treat water as a renewable resource?

2. What reservoirs of water might we tap if current sources become inadequate?

# The Atmospheric Cycle

## Lecture 41

**I'll focus on the atmospheric cycles of weather and climate, which are driven by the Sun's radiant energy. The outline of this lecture is straightforward: After reviewing the nature of cycles in general, and the water cycle in particular, we'll look at the atmosphere.**

Every physical system, including Earth cycles, must obey natural laws. Atoms are conserved, so the total amount of water on Earth is constant. If matter moves, a force must be involved. The force of gravity causes liquid water to run downhill. A source of energy, such as the Sun, is required to exert a force over a distance. Energy can change from one form to another. Heat used to evaporate water is converted to gravitational potential energy; we use some of that energy in hydroelectric power plants. Heat must spread out, in accordance with the second law of thermodynamics. Ocean currents transfer heat across the globe. The same principles apply to the cycles of atmosphere and rock.

Earth's atmosphere is a gas envelope hundreds of kilometers thick that surrounds the planet. The atmosphere only appears to be one continuous mass of air; it can be thought of as several different interacting reservoirs. At any one time the atmosphere can be divided into separate air masses, each of which has more or less uniform properties. Adjacent air masses may occupy different regions close to the ground or different atmospheric layers high above the surface, such as the troposphere and the stratosphere.

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**Snow is possible on mountain peaks in warm climates because of the temperature and pressure changes caused by altitude.**

Weather and climate are two closely related terms. Weather is the state of the atmosphere at a given time and place. Weather changes on a daily or hourly basis. Climate is a long-term average of weather for a given region. Climate may remain unchanged for centuries, or it may shift quite dramatically, often for reasons that are as yet uncertain.

Five variables define the state of the atmosphere: temperature, air pressure, humidity, cloudiness, and prevailing winds. First, the temperature refers to temperature at ground level. Temperature varies strongly with altitude above the ground. The major layers of the atmosphere are defined by these temperature variations. The troposphere extends up to 10–16 km and is defined by the zone of decreasing temperature with altitude. This is the layer that experiences extensive convection from the ground. The next layer, called the stratosphere, extends up to about 50 km. Temperatures in this zone increase, often by as much as 50 or 60°C, with altitude because small quantities of the gas ozone in this layer absorb much of the Sun's ultraviolet radiation.

**The atmospheric cycles of weather and climate are driven by the Sun's radiant energy.**

The second variable that defines the state of the atmosphere is pressure. Air pressure decreases significantly with altitude, because air is compressed by its own weight. Pressure also varies laterally. This occurs because air masses tend to move and rotate with respect to each other. Air piles up in some places to form a high-pressure system, while it stretches out in other places to form a low-pressure system. Air in low-pressure systems tends to rise, which causes cooling and increased clouds; conversely, high-pressure systems tend to feature warmer, dry air.

The third atmospheric variable is humidity, which is a measure of the atmosphere's highly variable water content. The bulk composition of the atmosphere is remarkably uniform. Two gases—nitrogen and oxygen—make up 99% of dry atmosphere. The atmosphere contains minor amounts of other gases, including argon, carbon dioxide, and traces of a dozen other gases. The atmosphere always contains some water vapor, though the amount is highly variable, depending on the temperature and relative humidity.

Cloudiness, the fourth atmospheric variable, is closely tied to humidity. Clouds represent a concentration of tiny water droplets or ice crystals. They form when air becomes saturated with water—a process that often occurs when a mass of air rises and cools. Clouds often dramatically outline the contact between two adjacent air masses. Dramatic anvil-shaped clouds often form when a warmer air mass collides with a cooler air mass. The warmer air mass is less dense, so it rides up over the cool air. This increase in elevation cools the warm, wet air, causing clouds and rain. Clouds and rain often form on the windward side of mountain ranges as an air mass is forced to rise up the mountain flanks.

The fifth atmospheric variable is the direction and strength of winds. Winds are a consequence of atmospheric convection, which helps to redistribute heat. Ocean breezes on a tranquil summer day illustrate how winds can occur. On a larger scale, the prevailing winds arise in the same way. The Sun heats air most near the Equator. That air rises and circulates toward the nearest pole, while colder air near the poles sinks and flows back toward the Equator. If the Earth did not rotate, prevailing winds near the Earth's surface would follow lines of longitude, from poles to Equator; winds at higher elevations would flow from Equator to pole. Earth's rotation complicates this pattern by sweeping out the north-south convection.

Climates usually change slowly on the scale of human lifetimes, but new evidence suggests that the Earth may occasionally experience short periods of dramatic climate change. Some scientists think we are now in a period of rapid global warming. Year-to-year measurements of global temperature in recent years indicate that the Earth is getting warmer at an alarming rate—perhaps several degrees per century. The 15 hottest years on record have occurred since 1980, and 1998 appeared to be the hottest year since record-keeping began in the 1870s. The average global temperature is extremely difficult to measure. The complexities of this research are epitomized by recent satellite data that erroneously seemed to be revealing an overall cooling in the lower atmosphere. By the most optimistic estimates, the global average temperature will rise at least 2°C by the year 2100. Others estimate

three times that increase. There very likely will be significant economic repercussions from these increases.

Whatever the cause, we must learn more about the factors that affect climate. One approach is paleoclimatology, the study of ancient climates. The distribution of fossil plants and animals provides important clues. Fossil pollen grains reveal the distribution of plants with distinctive habitats. Glacial deposits also provide clues. Ice cores from Greenland and Antarctica hold a continuous 250,000-year record of the atmosphere in the form of tiny air bubbles. Measurements of the isotopes of oxygen ($O_{16}$ and $O_{18}$) can tell us the temperatures. The ice core climate record seems to indicate that dramatic temperature changes can take place in very short periods. We don't know what caused these drastic changes, but we do know that a similar rapid warming today could have catastrophic effects on the world's ports that are near sea level.

The climate of a region is profoundly affected by details of the distribution of landforms and bodies of water. Several factors that strongly influence regional climate are now well documented. Large bodies of water and ocean currents can greatly change a region's climate by transferring heat. Mountain ranges disrupt the movement of air masses and can efficiently remove moisture from an air mass. These and other effects show that movement of tectonic plates plays a major long-term role in Earth's climate. Ultimately, then, the global cycles of water and air are tied to the great cycles of the solid Earth, which is the subject of the next lecture. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 18.

## Supplementary Reading

Skinner and Porter, *The Blue Planet*, Chapter 12–14.

## Questions to Consider

1. What is the climate where you live? Ask long-time residents of your area if they sense a change in climate during the last half century.

2. What effect would an average temperature increase of 5°C have on your area?

# The Rock Cycle

## Lecture 42

**In this lecture, you'll meet the three major classes of rocks: the igneous rocks, the sedimentary rocks, and the metamorphic rocks. We'll examine how these materials continuously cycle Earth's atoms from one reservoir to another.**

The Earth's first rocks were igneous, but sediments soon formed by weathering, and both igneous and sedimentary rocks were metamorphosed in the dynamic early Earth. Around the world, rocks have amazing stories to tell. The rock cycle is epic both in terms of time and scale. Geologists recognize three major rock types:

- Igneous rocks include all rocks that form from a molten state.
- Sedimentary rocks include all rocks that are deposited in layers.
- Metamorphic rocks include all rocks whose mineralogy is altered by the effects of temperature and pressure.

The Earth is a physical system with a long, complex, and largely unknowable history. That history conformed to physical and chemical laws, but it was influenced by countless random and unpredictable events. Our best opportunity to know Earth's past lies in studies of the rocks—the field of geology. Yet as permanent and unchangeable as rocks may seem, they, too, take part in a cycle of constant change. The rock cycle, which includes the formation, alteration, and destruction of the solid portions of the Earth's crust, is epic both in terms of time and scale. Rocks include almost all of the materials that make up the solid Earth. Most rocks are composed of numerous interlocking grains of different minerals (chemical compounds).

Geologists distinguish between volcanic rocks that solidify on the surface and intrusive rocks that solidify underground. Igneous rocks that cool very quickly, including most volcanic rocks, tend to be fine-grained or even glassy.

Examples include most basalts and obsidian. Intrusive rocks, which cool more slowly, often are more coarse grained. Granite is a common example.

Sedimentary rocks include all rocks that are deposited in layers, either as layers of particles, or as chemical precipitates in water. Sandstones are sedimentary rocks formed from sand, which accumulates at ocean margins and in deserts. Shales are formed from mud and silt, often on the deep, calm bottoms of lakes or oceans. Limestones form from the gradual buildup of calcium carbonate, either from the shells of dead animals such as coral or from slow chemical precipitation. Sedimentary rocks often hold fossils, the evidence of past life. The law of superposition states that younger layers are always deposited on top of older layers.

**Rocks reveal the complex history of Earth's landforms and life.**

Metamorphic rocks include all rocks whose mineralogy is altered by the effects of temperature and pressure. In an earlier lecture, we learned about phase transitions, such as the transformation of graphite into diamond deep within the Earth. Many minerals undergo such changes when subjected to high temperatures and pressures. Shales transform first to slate, then to schist, and finally to gneiss as they are more deeply buried and metamorphosed. Limestone metamorphoses to marble.

Earth's first rocks formed toward the end of the great bombardment. All of the earliest rocks must have been igneous, because the Earth cooled from a molten sphere of magma. The surface of the Earth was molten, red-hot lava. Slowly that surface cooled, and a black crust of volcanic rocks covered portions of the surface, which got thicker and thicker with time. Intense volcanic activity still covered much of the surface. Many of these volcanoes released less dense material with the composition of granite. These lighter rocks would eventually form the continents.

As the first igneous rocks were forming, volcanoes continued to spew gases such as water vapor, carbon dioxide, and nitrogen into the young atmosphere. Exposed rocks, subject to the atmosphere and the first rains, began to weather, breaking down into small particles that accumulated in low-lying areas as

layers of sediment. Sandy beaches may have formed along the shores of the first oceans as fine-grained sediments blew from land and settled into ocean basins. As these layers thickened and hardened, the first sedimentary rocks were formed.

Plate tectonic processes on the young, hot Earth must have been much faster than today. Igneous rocks were subducted deep into the mantle, where they were altered by temperature and pressure. Sediments were also buried and metamorphosed, or even melted to form new magma. Today, the cycle that forms igneous, sedimentary, and metamorphic rocks continues.

Geology, the science of rocks, is first and foremost a field science. When geologists go into the field they make observations and measurements on rocks. They measure and map the relative positions and thicknesses of different rock formations. They collect samples of rocks and return to their laboratories to analyze the minerals, and to record their ages with radiometric techniques.

Most of all, geologists think about history. Every outcrop of rock, every roadcut, has an ancient history. Because the Earth constantly recycles its rocks, most of that history is lost. The oldest oceanic rocks are not much more than 200 million years old. Subduction swallows up old ocean crust as fast as new crust is formed at mid-ocean ridges. Continental materials can be much older, because the continents float on top of plates. Nevertheless, relatively few rocks are older than 2 billion years. Thus, we know very little about the geology of the planet for the first half of its existence. On the other hand, thanks to the abundance of accessible rock formations, we know a great deal about the last billion years of Earth history.

As you drive past rock outcrops or road cuts anywhere in the world, the rocks have amazing stories to tell. I have a beautiful fossil-rich limestone from Cincinnati, Ohio. This rock was formed about 500 million years ago when the Cincinnati area was under a shallow tropical sea with coral reefs. They are examples of silicification, where silicon replaces calcium carbonate. Another fossil-rich rock from the foothills of the Appalachians in West Virginia was found on a steep outcrop of rock, with rock layers nearly vertical, at an elevation of 3,000 feet. The rock was laid down as fine mud in

a shallow sea about 400 million years ago. A piece of marble from Vermont tells another story, that of metamorphic transformation from sedimentary limestone to valuable marble.

A recurrent theme of geology is the abundance of life on Earth. We now turn our focus to living things—the most complex physical systems that we know. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 18.

## Supplementary Reading

Press and Siever, *Understanding Earth*, Chapter 9.

## Questions to Consider

1. Imagine the geological histories of some of the grains of sand on the beach.

2. What is the geological history of your region as revealed by the rocks near you?

# What Is Life?

## Lecture 43

**We have arrived at last at the most complex systems in the natural world: living systems. In the final 18 lectures of this series, I'm going to focus on life. Perhaps the first and most basic principle that separates life from nonlife is that all life on Earth has the ability to obtain matter and energy from its environment, to grow, and to reproduce with variations.**

It is useful to approach biological sciences in two stages. The first step is achieving an understanding of the basic laws of forces, motion, matter, and energy. The second step is applying that understanding to specific natural systems such as a living organism, which must obey these laws. In spite of thousands of years of study, no one definition of life has been widely accepted. Many traits associated with living things (movement, for example) are not observed in all life, while some lifelike traits are also exhibited by nonliving things.

A few traits shared by all known living organisms (such as growth) may be as close as we come to a realistic definition of life.

- All organisms are highly complex chemical systems, with thousands of interdependent molecular components. The simplest life form is far more complex than the most advanced products of human technology.

- All organisms are composed of cells, the unit of life in which metabolism occurs.

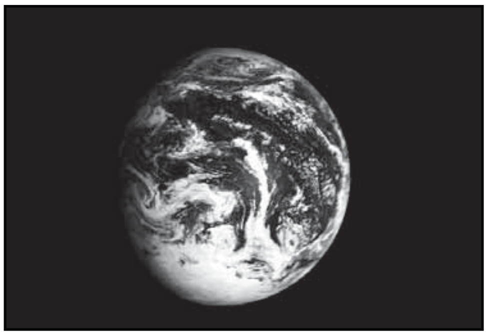
- All organisms obtain and use energy. Every organism needs energy to feed, to grow, and to reproduce.

- All organisms reproduce using the same genetic mechanism.

- All organisms grow and develop. Most organisms change form and capabilities as they get larger.

- All organisms respond to changes in their external environment while maintaining a relatively constant internal environment.

There are many different ways of thinking about living things. You might study an ant at smaller and smaller scales. With a microscope, you could identify the parts of an ant—its external segments and internal organs. You could study the ant at the cellular level, documenting how different cells perform different functions, or how the ant develops from a single fertilized ant egg. You could study the ant at the molecular level, deducing all the ant's chemical reactions. You could study the ant's genetic instructions carried by its DNA.



NASA.

**Geologists and astronomers see Earth as a planet; biologists see it as an ecosystem.**

Alternatively, an ant can be studied at larger scales. The ant is part of an ant colony, so you might study the behavior of the entire ant population. You might study the interaction of the ant colony with other interdependent species and their environment at the level of an ecosystem. At the largest scale, the ant is part of the global biosphere, which is intimately tied to Earth's systems of water, air, and rock. The diversity of approaches to biology explains, in part, why biology is a relatively fragmented discipline.

Biologists focus on all four broad categories of scientific questions—existence, origin, process, and applied. Existence questions—finding what organisms are out there—have played a central role in biology for thousands of years. Exploring expeditions of the 18th and 19th centuries always had a naturalist to describe plants and animals. The systematic treatises on life

forms that resulted from these voyages are among the most beautiful books ever published. Today, the search for new life continues in earnest, even in the most extreme of earth's environments. Scientists also search for life on other worlds.

The origin of life is a question of deep religious, philosophical, and scientific interest. The origin of life on Earth is an extremely ancient, and therefore inaccessible, event. The search for life on other worlds is closely tied to the search for origins.

Process questions that explore how organisms work are among the most basic problems in biology. Many studies in genetics focus on the function of genes—the coded instructions for individual enzymes. Developmental biologists deal with the extraordinarily complex processes by which a single fertilized egg becomes a multicellular organism. At a larger scale, ecologists investigate the interaction of different organisms in the context of their environment.

Applied questions play a special role in biological research, because we are living organisms. Medical research is by far the largest single scientific endeavor. Agriculture is another major area of applied biological research.

**All life on Earth has the ability to obtain matter and energy from its environment, to grow, and to reproduce with variations.**

Taxonomy, the formalized procedure for classifying and naming of life forms, plays an important role in biology. The unambiguous naming of physical objects is an essential step in scientific communication. Nomenclature was an especially severe problem in $19^{th}$-century mineralogy, when each nation's mineralogists and miners used their own idiosyncratic names. Sometimes, it is difficult to recognize a new phenomenon if you don't have a name for it.

The Linnaean system of nomenclature assigns a specific name to each kind of organism, according to a hierarchical classification scheme. This system works in much the same way as an address, with a sequence of more and

more specific categories. Similarly, in the Linnaean system, you define the kingdom, phylum, class, order, family, genus, and species. A common shorthand when dealing with organisms is to cite just the genus and species in what is called a binomial nomenclature. For example, humans are members of *Homo sapiens*.

The Linnaean system today recognizes five major kingdoms, though this number is subject to change. Monera are single-celled organisms without an internal structure called the cell nucleus. Some taxonomists want to split this kingdom into two, based on genetic evidence that there are two very different kinds of monera, the archaebacteria and the enbacteria. Protista are single-celled organisms with a cell nucleus. Fungi are multicellular organisms that get energy and nutrients by absorbing materials from their surroundings. Plants are multicellular organisms that get their energy from the Sun by the process of photosynthesis. Animals are multicellular organisms that get their energy and nutrients by eating other organisms.

It's not always a simple matter to tell what a species is. The simple definition is that two organisms are of the same species if they can breed to produce fertile offspring. This definition cannot be applied easily to some varieties of organisms or to fossil organisms. All life can be classified according to this system, but only a tiny fraction of all species are known. At present, something more than 1.8 million species have been identified. But there may be 50 million species. It is sobering to think how much we don't know about life on Earth. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 20.

## Supplementary Reading

Brun, McKane, and Karp, *Biology: Exploring Life*, Chapter 1.

Wilson, *The Diversity of Life*.

## Questions to Consider

1. If life arose independently on another world, must it display all of the characteristics of life on Earth?

2. What do you think might be some of the reasons why scientists have only identified a few percent of all species?

# Strategies of Life

## Lecture 44

**We're going to find that all living things have to adopt a strategy to compete for resources and survive variations in the environment.**

One useful way to understand the different kingdoms of life is to consider their distinctive lifestyles. Before considering differences in groups of organisms, it's important to look at the metabolic process that stores chemical energy in all life. Metabolism is the cell's process of obtaining energy from its surroundings and converting that energy into molecules. Several small molecules that act like batteries are used to store and transfer energy in every known cell. The most common molecular battery is called adenosine triphosphate, or ATP. ATP molecules are formed in one part of the cell, called mitochondria, and they are shipped to other places where they power the cellular machinery.

ATP molecules can be synthesized in several ways. One important process that occurs in all cells is called glycolysis, by which a molecule of the energy-rich six-carbon sugar glucose is split into two smaller fragments. Glycolysis is a complex, 10-step process, with each step governed by a biological catalyst, or enzyme.

Several other metabolic pathways, including respiration and fermentation, also produce ATP. Respiration is always preceded by glycolysis, which splits a glucose molecule into two pyruvic acid molecules. The pyruvic acid then enters a metabolic cycle called variously the citric acid cycle, the TCA cycle, or the Krebs cycle. Throughout the several steps of the Krebs cycle, carbon-based molecules are oxidized to produce $CO_2$ plus energy, which ultimately gets taken up in ATP or other energy-rich molecules. A single glucose molecule can be converted to as many as 38 ATP molecules. Fermentation is an incomplete reaction of pyruvic acid to alcohol or some other small carbon-based molecule in the absence of oxygen.

One-celled organisms might seem to be the simplest group in terms of survival strategies, but they are actually by far the most diverse. Single-celled

organisms live in many extreme environments—Arctic ice, near-boiling hot springs, in salt lakes, and deep underground in solid rock. Microbes get their chemical energy from an equally wide variety of sources. While most microbes live as isolated cells, some have the ability to organize into colonies that form large structures.

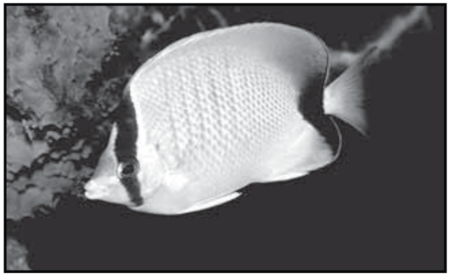
The kingdom of fungi includes mold, mushrooms, and yeast—all organisms that resemble plants in terms of their cell structure and growth patterns but are nonphotosynthetic. Fungi adopt a variety of survival strategies. Some fungi, like yeast, are single-celled organisms that can form bacteria-like colonies. They reproduce primarily asexually by the production of spores. Other fungi, including the molds, consist of myriad intertwined filaments that grow as fluffy masses. Lichens have a remarkable cooperative, or symbiotic, lifestyle, as fungi filaments intertwine with photosynthetic algae. Mushrooms are the only type of fungi that rely primarily on sexual reproduction.

**Metabolism is the cell's process of obtaining energy from its surroundings and converting that energy into molecules.**

Fungi play many important roles in nature and commerce. They help to decompose dead organisms and convert rock into soil. Through the process of fermentation, fungi facilitate the production of cheese, soy sauce, and alcoholic beverages. Many mushrooms are also edible. Fungi assist in the manufacture of many industrial products, including soaps and plastics. Penicillin and other antibiotics have saved countless lives.

Plants and algae obtain their energy from the light of the Sun, converting photons to chemical energy of their cells and tissues. All plants and algae use the chemical process called photosynthesis, by which solar energy is converted into energy-rich molecules such as the sugar glucose. The classification of plants is difficult and not at all a matter of universal consensus. Algae are especially problematic, because they can thrive as single-celled organisms, but they often form large colonies with plant-like structures, such as kelp. The main divisions of multicellular plants are based on the

way that they reproduce and how they circulate water. The simplest plants, called bryophytes, include the mosses; they absorb moisture directly through their above-ground structures, so they live in wet areas near to the ground. Most other plants are vascular plants that have roots, stems, and leaves—an internal plumbing system that moves water by capillary action. All plants can reproduce sexually, but they can also be cloned; that is, new genetically identical plants can often be grown from a single cell of an older plant.



Corel Stock Photo Library.

**Fish are members of the vertebrate phylum.**

Animals include multicellular organisms that obtain their energy and raw materials from the biomolecules of other organisms. Animals are remarkable for their diversity. More than 1.3 million living species of animals are known in about 35 distinct phlya, each of which represents a different basic design of internal and external structures. Vertebrates include all animals with a bony skeleton and a backbone that protects a spinal chord, such as fish, reptiles, amphibians, birds and mammals.

However, the vast majority of species are invertebrates, which include all animals without backbones. Invertebrates include sponges, jellyfish, corals, mollusks, and many kinds of worms. Arthropods, with jointed legs, number almost 1,000,000 known species, and many more are being found all the time. Insects account for 70% of arthropods, and beetles are the great majority of those. When the distinguished evolutionary biologist, J. B. S. Haldane (1892–1964) was asked what his decades of study had taught him about God, he replied, "He has an inordinate fondness for beetles." ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 20.

## Supplementary Reading

Attenborough, *Life on Earth*.

Brun, Kane, and Karp, *Biology: Exploring Life*, Chapters 36–39.

## Questions to Consider

1. Think about recent meals that you have eaten. How many kingdoms were represented? How many phyla?

2. From what sources did you get energy during the past 24 hours?

# Life's Molecular Building Blocks

## Lecture 45

**One of the surprising discoveries of biology is that all known life forms are based on the same types of chemical building blocks, the same reactions. They produce the same kinds of molecular structures. In fact, all living things are made from versatile carbon-based molecules.**

Living organisms are complex, but complex systems are often built from relatively simple parts. All known life forms are based on the same types of chemical reactions that produce the same basic types of molecular building blocks. Nutrition Facts information on the packaging of a favorite breakfast or snack food provides a sense of life's essential chemicals. Calories indicate the energy content of food. Fat, carbohydrate, protein, and a variety of vitamins and minerals represent the raw materials from which our bodies are made. Living organisms contain an amazing variety of materials: wood, muscle, seeds, skin, leaves, blood, and countless others.

**Organic molecules are no different in principle from other chemicals.**

In the early 19th century, conventional wisdom held that the molecules of life were formed by their own rules—perhaps governed by the life force. In 1828, German chemist Friedrich Wohler (1800–1882) demonstrated that organic molecules are no different in principle from other chemicals. Biochemical studies eventually led to the realization that all of life's varied chemical substances are constructed from a few molecular building blocks, which share four essential characteristics.

- Life's molecules are carbon-based.
- Life's molecules are formed from just a few different elements: hydrogen, oxygen, and carbon comprise more than 98% of life's atoms, while nitrogen and phosphorus are also essential elements.

- Life's chemical structures rely on modular construction. Life makes most of its chemicals from a few relatively simple building blocks.

- The function of life's molecular building blocks depends on their physical, three-dimensional shape. The geometrical shape of a molecule will determine how it interacts with adjacent molecules.

Carbohydrates, which are composed of carbon, hydrogen, and oxygen, are the most abundant biomolecules on Earth. These molecules are synthesized by plants from water and $CO_2$, and they play several roles in living things. The commonest carbohydrates are sugars, which typically have a single ring-like structure of 5, 6, or 7 carbon atoms. The most abundant sugar in nature is the six-carbon sugar glucose. Recall that glucose molecules play a central role in the metabolism of cells. Plants synthesize glucose by the process of photosynthesis, which uses the Sun's radiant energy to transform water plus carbon dioxide. Both plants and animals use the energy of glucose to make ATP. The energy of glucose is released by oxidizing the sugar molecule to release $CO_2$ and water in the process of respiration.

A single sugar molecule is called a monosaccharide. Two sugars often link together to form a disaccharide, while polysaccharides are long polymer chains formed from hundreds or thousands of sugar molecules. The two most common polysaccharides, cellulose and starch, are synthesized by plants from glucose. Both polymers serve structural roles in plants, but they use two different kinds of sugar-sugar linkages. Starch consists of an extensive glucose network of chains and branches, with C-O-C bonds linking every unit. These C-O-C bonds are somewhat flexible, so starch is not a strong structural material in plants. Digestive enzymes in humans and other animals can break down starch into individual glucose molecules for food.

Cellulose (or fiber in food packaging) is a polysaccharide of glucose that provides the rigid structural materials for tree trunks, plant stems, grass, leaves, and other vegetable material. In cellulose, each pair of glucose molecules forms a strong three-way bond. Humans and other animals are unable to digest cellulose. Wood-eating termites and grass-eating grazing animals rely on microorganisms that produce a special enzyme, called

cellulase, that attacks the cellulose bonds. Cellulose in the human diet provides necessary fiber.

Lipids, which include all fats, oils, and waxes, are characterized by their insolubility in water—a property that makes them ideally suited to forming cell membranes. This diverse group also finds use in cells as energy-storage molecules, as hormones that regulate the activities of organs, as light-absorbing pigments, and other specialized functions. All lipids are made from carbon and hydrogen, with a little bit of oxygen. The simplest lipids are called fatty acids. They have a hydrocarbon backbone of from 4 to 36 carbon atoms. One end of a fatty acid molecule is terminated by a carbon with three hydrogen atoms. This end is hydrophobic—it is repelled by water. The other end of the molecule is terminated by a COOH group. This end is hydrophilic—it is attracted to water. In some fatty acids the chain of carbon atoms has only single C-C bonds; that fatty acid is said to be saturated. Other fatty acids have double C=C bonds; these lipids are unsaturated. Fatty acids provide the building blocks for fat cells, which store energy and provide insulation.

Phospholipids are a vital class of lipids that are used to manufacture cell membranes. A typical phospholipid molecule looks a little like a bobby pin, with two long fatty acid units attached to a rounded end. The exposed ends of the fatty acids are hydrophobic $CH_3$ groups, while the rounded end incorporates a phosphate group (with phosphorus and oxygen atoms) that is hydrophilic. When a large number of phospholipid molecules are placed in water, they spontaneously rearrange themselves to reduce their energy. The solution used by all cells is to form a double layer of lipids—a lipid bilayer—with hydrophobic ends on the inside and hydrophilic ends on the outside. This arrangement effectively separates the insides of a cell from the outside. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 21.

## Supplementary Reading

Lehninger, Nelson, and Cox, *Principles of Biochemistry*, Chapters 9 and 11.

## Questions to Consider

1. What chemicals do you consume frequently that are not part of a regular diet? How do those chemicals affect you?

2. Keep a record of everything you eat over a period of several days. Using the nutritional information contained on food packaging, determine your average calorie intake per day. What percentage of those calories come from fat?

# Proteins

## Lecture 46

**Proteins exemplify the principle that structure determines function. With proteins, we again see the incredible complexity that's possible with carbon-based molecules, this astonishing range of form and function.**

Most of life's molecular building blocks share four key characteristics: They are based on carbon, they have only a few different kinds of elements, they are modular in design, and their shape determines their function. In this lecture we'll focus on proteins, the chemical workhorses of life. Proteins, more than any other kind of biomolecule, illustrate the astonishing complexity that can arise from assembly of a few simple modules.

All proteins are polymers of relatively small molecules called amino acids. All amino acids have a central carbon atom with four attachments.

- One attachment is always a hydrogen atom.
- One attachment is always a carboxyl group, C = O-OH.
- One attachment is always an amine group, $NH_2$.
- The fourth attachment, called the side group, can be almost anything from a single hydrogen atom to a carbon-based chain, ring, or branched structure.

Because the central carbon has four distinct attachments, most amino acids come in two distinct varieties—clockwise and counterclockwise, or left- and right-handed. The amino acids in our bodies are left-handed.

There are literally thousands of different possible amino acids; the variety is limited only by the variety of possible side chains. Only 20 different amino acids are found in living things. All proteins are formed from just this small

set. All amino acids in living things have the same handedness. The amino acids of life are a diverse group. They include side chains that are nonpolar, polar, negatively charged, positively charged, and neutral.

Life's amino acids take on interesting forms and functions when they begin to bond to each other—to polymerize. The most common chemical reaction involving amino acids is the formation of a peptide bond. Two amino acids can link together when the carboxyl group of one amino acid reacts with the amine group of a second amino acid. The OH of the carboxyl and one H of the amine form a water molecule, and the two amino acids link through a C-N bond. This is a condensation polymerization reaction. The resulting polymer can be any length, from two amino acids to thousands.

The nomenclature gets a little confusing here. In biological systems, a "peptide" or "polypeptide" is a small group of amino acids—perhaps two to a few dozen—linked by peptide bonds. Insulin is a hormone that is an example of a peptide. Proteins are generally larger polymers of amino acids, from perhaps a hundred to thousands of units long. Many proteins are also enzymes, a term that refers to the molecule's role in chemical synthesis.

**Proteins are the chemical workhorses of life; built from chains of amino acids, their structure determines their function.**

The function of proteins follows from their structure. Discovering a protein's three-dimensional structure is fiendishly difficult. The "simple" first step is defining the unique sequence of amino acids—the primary structure. Sequences of amino acids tend to adopt a number of common secondary structures—shapes such as open spirals, flat sheets, and loops. As a protein folds up, hydrogen bonds can pull together amino acids that are widely separated along the chain, creating a molecule of complex three-dimensional shape—the tertiary structure. Two or more folded amino acid strands may stick together to make one functional enzyme.

Determining the complete structure of a single protein molecule can take a team of researchers years to complete. It took 20 years to determine

the structure of hemoglobin. Presently, there is no way to predict protein structures, but computer technology offers some hope for doing this in the future.

The importance attached to understanding protein structure lies in the close relationship between a protein's folded shape and its cellular function. Structural proteins form a variety of supporting cable- and sheet-like materials, including hair, tendons, and cartilage. Most proteins serve highly specialized biological functions as enzymes, which are the reaction catalysts of biological systems. A synthesis enzyme, for example, will have grooves and furrows on its surface, called active sites, that exactly match the shapes of the target molecules. When two appropriate molecules attach to those spots on the enzyme's surface, the enzyme changes shape in such a way as to snap the two pieces together.

It is important to have adequate sources of proteins in your diet. Only 12 of the 20 amino acids are manufactured in the human body. The other eight so-called essential amino acids must be obtained from other organisms. Lysine is an example of the latter.

Food varies considerably in its protein content, from about 1% in bananas to 30% in some beans and dairy products. Not all protein-rich foods have amino acids in the same ratios as in human proteins. Foods that match human amino acid ratios are said to have high-quality proteins. Foods that don't have low-quality proteins. For example, animals generally have high-quality proteins, while plants often have low-quality proteins. Combinations of plants can provide a complete diet—a combination of grain and beans, for example. Tofu and rice form another such pair.

Let's take a closer look at the dietary information on the side of a food package. Calories represent the energy available from oxidizing carbon and hydrogen in fats and carbohydrates. These molecules can be "burned" by cells to produce energy plus carbon dioxide and water.

Total fat represents the weight of lipid molecules. All cells have cell membranes, so all food has some fat. Food differs, however, in the types of lipids—for example, in the amount of saturated versus unsaturated fats.

- Saturated fats have straight chains with all single C-C bonds.

- Monounsaturated fats have kinked chains with a single C=C double bond, while polyunsaturated fats have chains with multiple double bonds.

- Cholesterol, which appears just below the fat information, is a lipid molecule with four interconnected carbon rings that is obtained from fatty foods and is produced in the human liver. This molecule is required for the synthesis of cell membranes, but too much cholesterol can lead to obstruction of blood vessels and heart disease.

Total carbohydrates refers to the amount of sugar, starch, and fiber in the food product. We can digest both sugar and starch, but fiber (cellulose) passes through the gut without being digested. Artificial sweeteners, like fat substitutes, have molecular shapes that fool the taste buds into sensing sugar.

Nutritional information indicates the grams of protein, but not the breakdown of the 20 amino acids. Finally, the nutritional information includes much about various vitamins and minerals, each of which plays a specialized role and is required in small amounts by the body. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 21.

## Supplementary Reading

Lehninger, Nelson, and Cox, *Principles of Biochemistry*, Chapters 5–8.

## Questions to Consider

1. Go to your drug store and find out what over-the-counter amino acid supplements are available. What are the purported functions of those supplements?

2. Many inherited diseases result from an error of a single amino acid in the sequence of a protein. How might such an error affect the protein?

# Cells—The Chemical Factories of Life

## Lecture 47

**All life is based on chemistry; you and I are exquisitely complex chemical beings. But chemistry has to be done in a very carefully controlled environment, and this is why all living things are made of one or more cells which control the chemical reactions essential to life.**

Reductionism, the effort to understand the physical world in terms of its smallest subunits, has long been a central strategy of physics and chemistry research. Biologists long resisted this approach because it doesn't seem possible to reduce the complex behavior of plants and animals to the interactions of atoms. With the introduction of more and more powerful microscopes, however, reductionism has also contributed to biological thinking. The first step in this process was the discovery that all organisms are made of cells—the chemical factories of life.

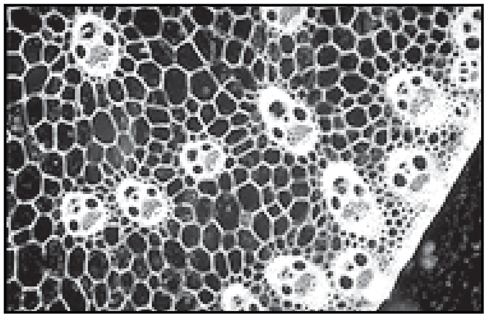
The discovery of cells was made by British physicist Robert Hooke (1635–1702), who was renowned for ingenious mechanical inventions and demonstrations. Hooke's most famous work was *Micrographia* (1665), in which he described and illustrated numerous original observations with the microscope. In *Micrographia* he observed the microscopic structure of cork, and he coined the word "cells."

In 1838, the German botanist Matthais Schleiden proposed that all plants are made of cells, and in the following year, his countryman, zoologist Theodor Schwann, extended this idea to animals by proposing the three tenets of cell theory, thus initiating the discipline of cellular biology.

- All living things are composed of cells.
- The cell is the fundamental unit of life.
- All cells arise from previous cells.

Cells are remarkably varied in size, shape, and function. Most cells are microscopic, some just a ten-thousandth of an inch, while some are quite large by comparison. All cells are bounded by a cell membrane; they have the ability to survive as isolated units and can perform all the functions of a living organism.

Biologists recognize two fundamentally different kinds of cells. Prokaryote cells are small, simple objects without any well-defined internal structures, such as a nucleus. All prokaryotic cells are bacteria, and all belong to the Monera kingdom. Eukaryote ("true nucleus") cells are generally much larger, with a nucleus and other discrete internal structures, called organelles. All plants, animals, fungi, and protists are made of eukaryotic cells.



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**A microscopic view of plant cells.**

Improved microscopes were the key to understanding the internal structures of cells. Scientists use two principal types of microscopes to study cells. Optical microscopes can magnify about 1,000 times, enough to resolve objects as small as 10 millionths of an inch. Light microscopes can thus reveal all cells, but not the smaller structures inside cells. Electron microscopes use a finely focused beam of electrons that passes through an extremely thin sample. Magnifications of 1,000,000 times allow observation of details of the cell's architecture, including individual molecular structures within the cell. Advances in microscopy have demonstrated that cells have extremely complex internal structures. These structures are isolated from the environment by a cell membrane, which is studded with receptor proteins, which provide doorways for food to enter the cell and waste to be excreted.

Inside the eukaryotic cell are found numerous separate structures called organelles. Each organelle is itself surrounded by a cell membrane, and each performs a specific function in the cell. The nucleus is the largest organelle. It

contains the cell's genetic blueprint—the instructions for all of the chemical operations the cell needs to build copies of itself. Several organelles play key roles in assembling and distributing proteins, lipids, and other cellular materials.

Organelles also play the central role in energy production in the cell. Mitochondria are the miniature power plants of all eukaryote cells. They convert energy-rich carbohydrates such as glucose into the compact battery-like molecule ATP. ATP molecules literally plug into other cellular molecules to provide the energy for work. Mitochondria are most abundant in cells that do mechanical work, such as muscles, where a steady supply of energy is required. Chloroplasts are organelles found only in plants and photosynthetic one-celled organisms. Chloroplasts use sunlight to synthesize sugars from water and $CO_2$.

**All living things are made of one or more cells, which control chemical reactions essential to life.**

Cells are the chemical factories of life. Cells exist to gather enough raw materials and energy to make copies of themselves. Like every factory, the cell has certain key structures. The cell membrane represents the walls of the factory, while receptors are the loading docks and doorways. The cell nucleus is like the main office, where all the blueprints and maintenance records are kept. Other organelles are part of the machinery that manufactures all the pieces required to build more cells. Mitochondria and chloroplasts are analogous to the cell's power plants.

The complex structure of eukaryotes, with small membrane-bound organelles, has led University of Amherst biologist Lynn Margulis to a fascinating theory of their origins. Margulis suggests that eukaryotes evolved more than 2 billion years ago from relatively large prokaryotes that incorporated smaller prokaryotes inside them. Some modern bacteria live inside eukaryotes, forming a similar kind of partnership. Mitochondria and chloroplasts contain their own DNA, and they divide independently of the main cell. The molecular mechanisms that make proteins in mitochondria and chloroplasts resemble prokaryotes more than eukaryotes. Chloroplasts have several other structural and chemical similarities to photosynthetic bacteria, which are assumed to be very ancient based on microfossils.

Cells are remarkable not only in their chemical complexity, but also in their ability to specialize. Adult humans have tens of trillions of cells, with several hundred different kinds of cells in the body. Each of these cell types performs a different chemical or structural function by producing a different suite of enzymes. Under most circumstances, bacterial cells all look and function alike.

Multicellular animals and plants, on the other hand, require specialized structures. Nerve cells, or neurons, act as wires that convey electrical impulses. Muscle is composed of many elongated cells that form fibers. Red blood cells, which transport oxygen from the lungs to all other cells, are the simplest and most abundant cells in the body. Several types of white blood cells combat infections, consume cellular debris in the blood stream, and produce antibodies that attack foreign cells and viruses. The most remarkable aspect of this cellular differentiation is that every multicellular organism begins as a single cell—a fertilized egg. The reductionist approach to life would suggest that something even smaller and more fundamental than the cell is controlling life's chemistry. In the next lecture we will begin our investigation of the unit of genetic information—the gene. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 22.

## Supplementary Reading

Brun, McKane, and Karp, *Biology: Exploring Life*, Chapter 5.

## Questions to Consider

1. Using cellular biology as an example, what is the role of new technology in the scientific process?

2. Make a list some of the other kinds of cells in the human body not discussed in the lecture.

# Gregor Mendel, Founder of Genetics

## Lecture 48

**In many respects, the central function of life is to produce more life, and the central problem in reproduction is information. How do you pass information from one generation to the next?**

Genetics is the study of the ways by which biological information is passed down from parents to offspring. This process of information transfer has continued unbroken from the first living cell nearly four billion years ago to the diversity of modern life. Without information there could be no life. To construct a living thing requires vast amounts of information about molecular building blocks, body architecture, and the dynamic processes by which organisms develop and reproduce.

In a sense, all life forms represent solutions to the problem of passing this information from one generation to the next. Genetics is the study of the ways by which biological information is passed down from parents to offspring. At the instant of conception, all of the information necessary to create a unique human being unites in the fertilized egg, an object about a hundredth of an inch across. As that first cell divides and an embryo develops, this coded information must be duplicated and read time and time again. Each individual may eventually pass on a portion of his or her unique genetic message to subsequent generations. This process of information transfer has continued unbroken from the first living cell nearly four billion years ago to the diversity of modern life.

**Each parent contributes genetic information to offspring.**

For centuries, scientists and philosophers have wondered how the vast amount of information necessary to produce a living organism could be stored, duplicated, and interpreted in an object as tiny as a cell. As our understanding of life's genetic mechanism deepens, we are beginning to learn ways to modify life at the molecular level. New genetic technologies hold fantastic opportunities, as well as great risks. But

before embarking on an investigation of molecular genetics, we must first set the historical stage.

Classical genetics is the study of how biological information is passed from parents to offspring at the level of organisms and their traits. For thousands of years, humans have taken advantage of the fact that “like begets like.” This phenomenon has been exploited since prehistoric times in the selective breeding of domesticated animals. New varieties of cultivated plants were developed in many places around the world. Ancient scholars also noted that certain diseases (which were quite real) and undesirable characteristics (easily imagined) run in human families.

The doctrine of spontaneous generation, a tenet of the teachings of Aristotle, claimed that inanimate matter was imbued with a life force and that life thus arises spontaneously all around us. This idea hindered progress in genetic understanding. The relationship between flies and maggots was clarified experimentally in 1668 by the Italian naturalist Francesco Redi (1626–1697).

Important contributions to the spontaneous generation debate were made by the amateur Dutch scientist Anton van Leeuwenhoek (1632–1723), who was the first to make extensive use of the microscope in the 1670s. Much of van Leeuwenhoek’s effort was directed toward a refutation of the doctrine of spontaneous generation. He was the first to observe microorganisms, and he observed sperm cells in semen. He suggested that every sperm contains a complete, miniature human. In the 19$^{th}$ century, it was finally demonstrated that animals and plants reproduce sexually, but the mystery of how a fully formed plant or animal develops from a single fertilized cell remained.

Johann Gregor Mendel (1822–1884), a Czechoslovakian monk, was the founder of classical genetics. Mendel entered the Augustinian monastery of Brno, in modern-day Czechoslovakia, at the age of 21 and took the name Gregor. The monastery actively promoted study and learning, and it had an experimental garden. During his training at the monastery, Mendel learned much about sheep breeding and hybridization of plants. His famous genetic research was undertaken between 1856 and 1863 in the monastery garden.

He focused his genetic research on seven distinctive traits of pea plants, such as flower color and plant height.

Mendel began his experiments by studying single traits. He established populations of pure-bred plants that always produced short or always produced tall plants, for example. Pea plants are normally self-pollinating, but Mendel removed the male sex organs from the plants he wanted to study and hand-pollinated these plants with pollen from a pre-selected father. For example, he performed a series of experiments in which he cross-bred tall and short pea plants.

The first generation of hybrid plants were all tall. Mendel said the tall trait is "dominant" over the short trait, which is "recessive." For every pea plant characteristic, Mendel identified a dominant and a recessive trait. Cross-breeding the tall hybrid plants led to a new pattern: about 1/4 of their offspring were short, while 3/4 were tall. In the next generation, the short plants bred only short plants, but the tall plants still bred a mixture of tall and short.

Mendel then did experiments where he considered combinations of two traits at once—for example, round versus wrinkled seeds, and yellow versus green seed color. Round shape and yellow color are the dominant traits. He found a distribution that out of every 16 plants, on average 9 had round-yellow seeds, 3 had round-green seeds, 3 had wrinkled-yellow seeds, and only 1 had wrinkled-green seeds. Mendel showed that this distribution was exactly what you'd expect if the two traits were completely independent.

Mendel performed more than 28,000 individual experiments to determine this behavior. From this vast accumulation of data, Mendel derived four key ideas, which might be called the four laws of classical genetics. There exist "atoms of inheritance," what we now call genes, which carry traits. Each parent contributes half of an offspring's genes; each individual, therefore, carries two genes related to each trait. Genes come in different forms, what we now call alleles. Some alleles are dominant and some are recessive. When both alleles are present, the dominant one is always expressed. Different alleles are sorted and distributed randomly. All combinations of alleles are equally likely.

These principles can be illustrated in a square diagram.

A pure-bred tall plant can be designated TT, while a pure-bred short plant is tt:

| | T | T |
|---|---|---|
| t | Tt | |
| t | | T |
| | t | |
| | Tt | |
| | | T |
| | t | |

Every offspring is a hybrid, designated Tt. Cross-breeding two hybrids yields a different pattern:

| | T | t |
|---|---|---|
| T | TT | |
| t | | t |
| | T | |
| | Tt | tt |

On average, out of every four offspring, three will be tall (two Tt and one TT) and display the dominant trait, and one will be pure-bred short (tt). Mendel announced his findings at a meeting of the Natural Sciences Society of Brno in March 1865. The paper was published the following year in the Society's widely distributed, but seldom read, journal.

Many aspects of classical genetics can be applied to our own species. Some human traits display the same trends that Mendel discovered in pea plants. Brown eyes are dominant over blue eyes; the ability to curl the tongue is dominant over the inability to curl the tongue; the presence of extra fingers is dominant over five fingers; color vision is dominant over color-blindness. Many genetic diseases also stem from a specific gene.

However, many human traits are not simply tied to one gene. Tallness and shortness in humans is a complex function of many genes. Most other human traits are similar: Physical attributes, intelligence, and behavior may all be influenced by combinations of many genes, along with the environment in which those genes are allowed to develop. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 23.

## Supplementary Reading

Gonick and Wheelis, *The Cartoon Guide to Genetics*.

## Questions to Consider

1. Mendel's work is now seen as a turning point in the history of genetic research. What factors might have led to his work being ignored in his own time?

2. Identify traits that you share with your parents or your children. What traits differ?

# The Joy of Science (Lectures 49–60)

**Scope:**

Part V of this lecture series focuses on the great unifying biological principles of genetics, evolution, and ecosystems. Biology was transformed in 1952 by the discovery of the elegant double helix structure of DNA, the molecule that carries the genetic code (Lecture 49). The genetic code is interpreted by the closely related molecule, RNA. All organisms use RNA to manufacture proteins from the genetic information carried by DNA (Lecture 50). Every individual has a unique genetic makeup, or genome (Lecture 51). Biologists are now learning to edit the genetic code, to modify organisms to produce chemicals or improve agriculture (Lecture 52). Genetic engineering of humans may some day be used to cure cancer and other diseases that arise from errors in our genetic makeup (Lecture 53).

The origin and evolution of life occurred in two stages. Life arose from air, water, and rock by chemical reactions during the first stage of chemical evolution (Lecture 54). Once life appeared, the second stage of biological evolution began. Abundant evidence demonstrates that life has changed over more than 3.5 billion years of Earth history (Lectures 55 and 56). Charles Darwin developed the theory of evolution by the process of natural selection (Lecture 57).

All individuals are part of ecosystems, which are complex communities of organisms and their physical environment (Lecture 58). Human activities can affect the global environment, often in ways that are difficult to predict. The ozone hole, acid rain, and the greenhouse effect are examples of human influences on regional and global environment (Lecture 59).

No one can predict what we don't know we don't know. Even a cursory review of today's most compelling scientific questions promises centuries of research adventure and discovery (Lecture 60). ■

# The Discovery of DNA

## Lecture 49

**We're going to explore the seminal discovery in modern genetics: that DNA, the double helix, carries the genetic code. In this lecture, I have two principle objectives. First, we're going to consider cellular genetics and the microscopic chromosomes. … Then we're going to see how scientists discovered the chemical identity of the genetic molecule, DNA.**

Cellular genetics is the study of the transfer of biological information at the level of cells. The principles of classical genetics, in particular the discoveries of the Czechoslovakian monk Gregor Mendel on pea plants, set the stage for discoveries at the cellular level. Mendel's work raised new questions in genetics.

- What is the physical and chemical nature of Mendel's "atoms of inheritance," which must carry biological information?
- How is the biological information stored, interpreted, and passed on from one generation to the next?
- How do alleles vary to yield different traits?

New insights were provided by examining reproduction at the cellular level. Two key microscopic discoveries set the stage.

- Every living thing is made of cells.
- All cells arise from the division of previous cells.

While observing cell reproduction, scientists noted the striking behavior of elongated structures in the nucleus, called chromosomes. Most cells divide by the process of mitosis, in which one parent cell becomes two identical daughter cells. Just before cell division, the chromosomes thicken and arrange themselves in pairs that line up as if along the equator of the nucleus.

The pairs of chromosomes are pulled apart toward opposite poles. Two new nuclei form where before there was one, as a new cell membrane divides the original nucleus in two.

The different process observed in sexual reproduction provides a key to understanding genetic mechanisms at a cellular level. Each species has a characteristic even number of chromosomes in almost every cell. Sex cells have only half the usual number of chromosomes. In 1902, the American biologist Walter Sutton (1877–1916) discovered that the 11 chromosomes from the eggs of female grasshoppers have matching pairs in the 11 chromosomes from the sperm of males. Sutton was able to equate each of Mendel's laws to the behavior of chromosomes, which were assumed to carry genes. To obtain a single set of chromosomes, sex cells must undergo a special process called meiosis.

Close examination of chromosomes revealed that human males carry one pair of chromosomes that is not exactly matched. One is longer, called X, while the other is shorter, called Y. Males have XY, while females have XX. This is the only genetic difference between males and females. Half of a male's sperm carries an X chromosome, while half carries a Y. Since all human eggs have an X chromosome, there is a 50:50 chance for a boy or a girl. Different living organisms (e.g., insects, birds) use different chromosomal strategies.

A major challenge facing biochemists was to discover the relationship between genes and the biomolecules that make up an organism. By the 1940s, it had been well established that proteins are the chemical workhorses of life. They serve as enzymes, structural building blocks, transport molecules, and hormones. In all of these capacities, the shape of the protein molecule is paramount. Proteins are constructed from a chain of amino acids, which then folds into a compact shape. Twenty different amino acids combine to form all of the thousands of different proteins; each distinct sequence of amino acids forms a different protein. A single mistake in the amino acid sequence, called a mutation, may cause the protein shape to be altered, rendering it unable to perform its catalytic or structural function. Sickle cell anemia is one such example. Studies of the genetic behavior of cells in which certain enzymes were mutated revealed that one gene corresponds to one specific protein.

The behavior of chromosomes and their genes transformed Mendel's idea of atoms of inheritance from an abstraction to real physical structures in the cell. Each chromosome is a long structure with a series of genes that can be mapped, like towns along an interstate. Since each chromosome holds many genes, this model called into question the fourth "law" of Mendel, that genes are expressed independently of each other. If two genes are on different chromosomes, then they are expressed independently, as Mendel observed. But if two genes happen to be on the same chromosome, then those two traits will follow each other much more closely and will not be independent.

Studies of the chromosomes at the molecular level were required to elucidate the mechanisms of genetics. The first step was to purify and identify the chemical substance that makes chromosomes. Chromosomes are made of two chemicals: proteins and deoxyribonucleic acid (DNA). In the early 1940s, the Canadian biologist Oswald T. Avery (1877–1955) managed to isolate and purify genetically active material and found it to be pure DNA. DNA contains a 1:1:1 ratio of three molecular building blocks: the 5-carbon sugar deoxyribose; phosphate; and four different bases—adenine, cytosine, guanine, and thymine (abbreviated A, C, G, and T).

**DNA—the "double helix"—carries the genetic code.**

Purified DNA was crystallized for study by X-ray diffraction. British crystallographer Rosalind Franklin (1920–1958) obtained the first X-ray photographs of DNA in the early 1950s. Franklin suggested that the phosphate molecules are on the outside of DNA and that the structure has aspects of a helix, like a spiral staircase.

In 1952, building on Franklin's studies, James Watson and Francis Crick solved the DNA structure. Watson and Crick discovered that the structure featured a double helix, something like a long, twisted ladder. Alternating sugar and phosphate molecules form the vertical sides of the ladder, and the bases (attached to the sugars) point from the sides to the center so that pairs of bases, either C-G or A-T, form the ladder rungs. A only forms rungs with T; C only with G. In fact, A and T are repelled by C and G. This feature explains why molecular ratios of A:T and C:G are always 1:1. This ladder-like structure is twisted into a double helix.

Watson and Crick immediately recognized that the power and beauty of the elegant DNA structure lies in its ability both to store and to copy vast amounts of information. Biological information is stored using a four-letter molecular alphabet. DNA copies itself by separating the double helix into two single strands and filling in the missing bases on each half. A ladder-like structure with variable rungs could at once store and duplicate vast amounts of biological information. Scientists had found the book of life, but a great challenge lay ahead. They had yet to learn how to read the genetic language. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 23.

## Supplementary Reading

Berg and Singer, *Dealing with Genes*.

Gonick and Wheelis, *The Cartoon Guide to Genetics.*

Watson, *The Double Helix*.

## Questions to Consider

1. There are 26 letters in the English language. Devise a code using only A, C, G, and T to communicate in English.

2. Rosalind Franklin did not share in the Nobel Prize with Watson and Crick. Investigate her life and work, and explore some of these reasons why her work was not so recognized.

# The Genetic Code

## Lecture 50

**DNA, the double helix, stores genetic information, but storing information is only half the genetic battle. You also have to be able to take that information and make molecules, make the chemicals of life. For that critical task, all organisms use RNA.**

Of all the scientific discoveries of the 20th century, none has had a greater impact than the deciphering of the genetic code. The DNA breakthrough unified genetics by providing a conceptually simple chemical basis for storing and duplicating hereditary information. The scientific community embraced the Watson and Crick model immediately upon its publication. The discovery of DNA's structure marked a historic transition point in the biological sciences.

Whatever the nature of the genetic code, it somehow had to convert the four-letter alphabet of DNA (A, C, G, and T) into the correct sequence of the 20 amino acids for each protein. Progress was made by studying mutations. Some mutations were known to result in the replacement of one amino acid with another in particular proteins. By documenting and comparing different mutants of the bacterium *E. coli*, geneticists surmised that genetic words were likely to consist of three DNA bases in a row, each three-letter word corresponding to one of the twenty amino acids. A gene is a DNA segment that codes for one protein by specifying the exact amino acid sequence.

During a decade of intense research, biologists struggled to deduce details of the process by which a DNA sequence leads to the synthesis of a protein. They discovered that synthesis depends on another molecule, ribonucleic acid, or RNA, which is closely related in structure to DNA. Each RNA is a single-stranded molecule similar to the double-stranded DNA, except that the sugar ribose substitutes for deoxyribose and the base uracil (U) substitutes for thymine (T).

Three forms of RNA participate in protein synthesis. First, messenger RNA copies the base sequence of a DNA segment (a gene) letter by letter. In this

process, an enzyme opens a DNA strand in the middle like a broken zipper. RNA nucleotides quickly fill in to form a copy of the information from only one side of the double helix. Each messenger RNA molecule is thus a long, single-stranded molecule that carries information about one gene. By using synthetic RNA chains as messenger RNAs, scientists deciphered the genetic code in the early 1960s. The complete genetic vocabulary consists of 64 different words, or "codons"—all possible three-letter combinations of A, C, G, and T (or U)

**All organisms use RNA to manufacture proteins from the genetic information carried by DNA.**

The genetic code defines the one-to-one correspondence between three bases on the one hand and an amino acid on the other. The next step was to deduce the cellular mechanism by which the information of messenger RNA serves as a template for protein synthesis. Two other RNA types, called transfer RNA and ribosomal RNA, play central roles in the cell's machinery that synthesizes proteins. Transfer RNA molecules have an amino acid attached to one end of the chain and three exposed bases on the other. The ribosome, which includes ribosomal RNA and about 50 proteins, provides the chemical machinery for linking the amino acids together to form a protein. What is perhaps most remarkable is that every living thing uses the exact same genetic mechanism. Human genes can be inserted into yeast or *E. coli*, and the appropriate protein will be produced.

Every human being has about 80,000 genes, each a genetic instruction manual that carries coded information for one protein. One of the greatest challenges in modern biology is to identify each of those genes, along with the structure and function of the associated proteins. The Human Genome Project addresses this mammoth problem in molecular biology and information technology. The project's two objectives are to provide a detailed map for the distribution of genes on each of the 23 pairs of human chromosomes and to determine all 3 billion letters of the human genetic message. After the sequencing is completed, there remains the mammoth task of determining the function of each human protein. This task will set an agenda for biology throughout the next century and beyond.

You can get a sense of a genome by focusing on one of the simplest of all gene-carrying entities, a virus. A virus is a strand of DNA (or messenger RNA, in the case of retroviruses) surrounded by a coating of proteins. Viruses are either the simplest living things or the most complex nonliving things. They are not composed of cells, and they cannot survive independent of a host cell. But under the right environment, they can reproduce and evolve. Viruses have several distinctive properties.

- A virus requires a host cell to perform virtually all of its functions.
- It is not capable of independent metabolism.
- It is much smaller than the smallest cell.
- It possesses either DNA or RNA, which carries the viral genome. In a retrovirus, the messenger RNA strand is converted to DNA by a special enzyme called reverse transcriptase.
- When taken into the host cell, the virus disintegrates. The viral nucleic acid takes control of the cell's genetic machinery to make hundreds of new viruses before the cell dies.

Viruses work by fooling the host cell into thinking that the protein coating is food. Receptors in the cell membrane "open the doors," so to speak. The virus attaches itself to the cell and injects its nucleic acid into it. The cell's polymerase replicates the viral DNA over and over again, making hundreds of copies. Since all life uses the same genetic code, the cell cannot distinguish the viral DNA from its own. The cell's genetic machinery is co-opted by viral DNA into making new viruses. The cell eventually bursts and dies, releasing the new viruses to search for new host cells. A typical viral genome, that of simian virus 40 (SV40), illustrates how the genetic code works.

Numerous viral diseases have been the subject of intensive research. Unlike DNA in our cells, viral DNA has no correction mechanisms. Therefore, viruses mutate extremely quickly, and viral diseases are constantly changing. More than 100 strains of rhinovirus, which causes the common cold, have

been isolated. Immunity for any one strain may not be effective against other strains. Similarly, every year there appear new strains of influenza virus. Physicians try to anticipate the spread of new types with each year's flu vaccine. HIV, the retrovirus that causes AIDS, attacks immune system cells, so that the body loses its ability to immunize itself against other infections—the ultimate cause of AIDS death. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 23.

## Supplementary Reading

Berg and Singer, *Dealing with Genes*.

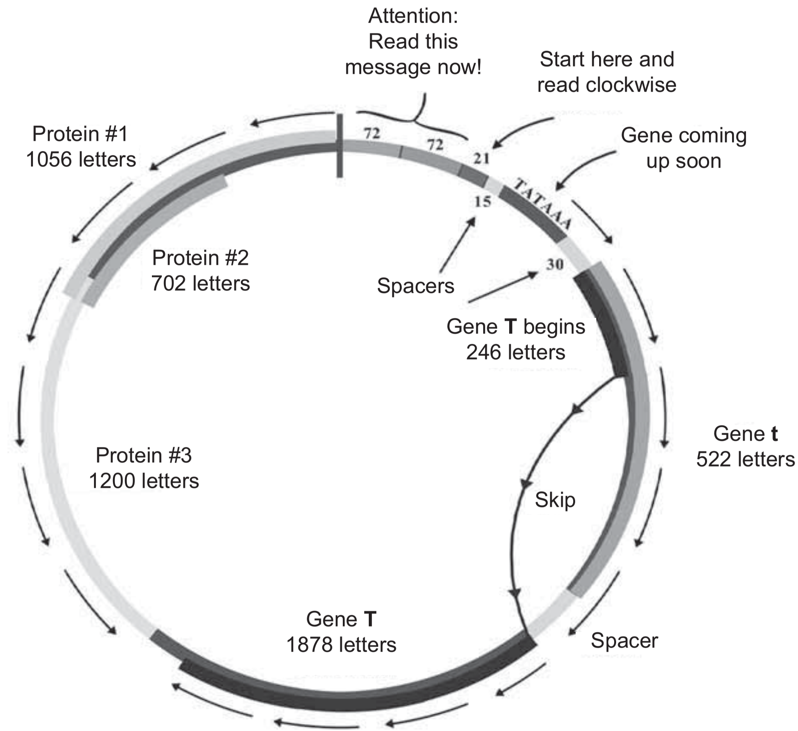
Gonick and Wheelis, *The Cartoon Guide to Genetics*.

## Questions to Consider

1. What might be the advantages, or disadvantages, of the redundancy in the genetic code?

2. What strains of flu are expected to be especially infectious this season? Ask your physician to explain how a flu vaccine is prepared.

Simian Virus 40
Genome Map Schematic



# Reading the Genetic Code

## Lecture 51

**In this lecture, I want to tell you about two dramatic developments related to our newfound understanding of the genetic code and its application to the study of humans. First, I'm going to focus on genetic fingerprinting and genetic testing; these are technologies facilitated by the polymerase chain reaction, or PCR. Then I'm going to consider the extremely controversial and ethically challenging field of behavioral genetics.**

The genetic code, carried in the four-letter alphabet of DNA and translated to form proteins by RNA, is shared by every known life form on Earth. Scientists now have the ability to differentiate the unique genetic pattern of almost every human individual, often on the basis of DNA contained in just a few cells. Genetic fingerprinting makes possible the identification of an individual from the genetic material in a single cell.

All humans have the same set of genes arranged in the same way on our 23 pairs of chromosomes. But among the 3 billion base pairs, millions of individual differences exist—typically once in every few hundred base pairs. While some of these differences are significant and are responsible for inherited diseases, the vast majority of changes are consistent with a fully normal person. DNA fingerprinting is now used routinely in legal proceedings. Genetic tests provide incontrovertible evidence of contested paternity and family lineage.

Detection of certain gene mutations is a reliable indicator of some inherited diseases. Our ability to manipulate and analyze tiny amounts of DNA rests on a simple and elegant technique called the polymerase chain reaction, or PCR. PCR targets a specific, short segment of DNA and makes countless copies of that specific segment. Scientists prepare a solution that contains the DNA sample of interest. To this solution are added significant amounts of three key ingredients: individual DNA nucleotides (individual rungs of the DNA ladder), an enzyme called polymerase that helps to assemble the DNA strands from the nucleotides, and numerous copies of short "primer"

segments of DNA that recognize and bond only to the desired sequence of perhaps twenty bases that marks a target gene or other DNA segment. This solution is heated to about 200°F, just below the boiling point of water—a temperature sufficient to separate double-stranded DNA into free floating single strands. Then the mixture is cooled to about 140°F—cool enough for two of the primer strands to bind to the target segments of the two exposed single DNA chains in the target gene. Polymerase triggers the growth of two new DNA strands, but only from the short segments targeted by the primers. The process is repeated over and over again. Within a few hours, millions of copies of the target gene sequence have been produced.

The polymerase chain reaction has found many applications in science and technology. In the most publicized uses, forensic specialists use PCR to amplify small amounts of DNA associated with a crime scene. PCR also provides the molecular biologist with a powerful tool to identify and understand genetic characteristics useful in medical research.

**Every individual has a unique genome.**

PCR is playing an important role in understanding how a gene works, by documenting the protein structure for which it codes. The first step is to find the location and sequence of a gene on a strand of DNA. Some genes are complexly arranged on the chromosome. Many human genes, for example, are broken into several widely separated segments on a chromosome with one or more intervening DNA sequences that are not part of the gene. Scientists do not understand completely how to read those convoluted DNA editing instructions. Therefore, it is often very helpful to have a copy of the messenger RNA, rather than the gene itself, to expedite understanding of protein structure. Scientists take advantage of enzymes called “reverse transcriptase” to make a DNA copy of a messenger RNA strand. These enzymes use a single-stranded messenger RNA molecule as a template to make a DNA molecule.

Each strand of messenger RNA contains the complete instructions for manufacturing one protein. While the original DNA gene may contain intervening sequences, the messenger RNA is an exact and correct genetic

message, without all the extra DNA. A strand of complementary DNA can be amplified by PCR and then sequenced to reveal the protein structure.

Our ability to read an individual's unique genetic heritage, and our growing understanding of the specific functions of genes, raises troubling ethical questions. Genetic factors play an important role in who we are and what we do. There exist incontrovertible links between human behavior and genes. These links were discovered essentially by accident, in studies of drugs, illness, and other seemingly nonbehavioral phenomena. Equally important is the recognition that while defects in single genes are sometimes sufficient to cause specific diseases, complex behavior and ability must arise from interactions of many genes, in addition to many environmental factors.

Animals provide a means to study behavior without raising many of the difficult social and political concerns associated with human behavioral research. Selective breeding of domesticated animals demonstrates that behavior is determined in part by heredity. Research on mutant fruit flies indicates that numerous genes participate in the routine functioning of the fly's nervous system. Mammals display behaviors far more complex, but pure-bred strains of aggressive and fearful laboratory mice have been produced. Studies of "knockout mice," in which researchers inactivate a specific gene, also reveal clear links between mouse behavior and genes.

Human subjects are more difficult to study than mice. This research depends on three assumptions:

- Behavioral and personality traits can be ranked, at least in a qualitative way.
- Environmental factors influencing behavior can be identified.
- Distinctive genetic characteristics of individuals can be quantified.

If all three assumptions of behavioral genetics are valid, then statistical tests may establish definitive links between heredity and personal traits.

Scientists, like the public at large, are strongly divided over the ethical implications of behavioral genetics. Proponents see this research as the best hope for understanding and ameliorating antisocial behavior. If one adopts a more conservative agenda, then findings of behavioral genetics will be equally reassuring. Genetic traits, it will be argued, absolve society of responsibility for poverty, crime, and drug abuse. Behavioral genetics forces us to confront the fact that we are, in essence, chemical beings—vastly complex, adaptable, unique, and unpredictable to be sure, but chemical nonetheless. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?* Chapter 13.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 24.

## Supplementary Reading

Berg and Singer, *Dealing with Genes*.

## Questions to Consider

1. What restrictions are placed on the collection and use of DNA evidence in your state or province? What recent court cases have relied on this kind of evidence?

2. Most children in the United States are given IQ tests. Is there any fundamental difference between the current type of written test versus genetic tests for intelligence that will probably be developed in the next century?

# Genetic Engineering

## Lecture 52

**I'll begin by reviewing what we've learned about the genetic code so far, and the whole field of modern molecular genetics. Then I'm going to focus on extraordinary new technologies that allow us to modify, or engineer, genetic material. Then we're going to see how these technologies are applied to microbes and to plants and consider the much more difficult aspects of genetically engineering animals, including human beings.**

Of all the scientific discoveries of the 20th century, none has had a more profound effect on our perception of the physical universe and our place in it than the deciphering of the genetic code. Humans, never content simply to observe nature, have begun to read and edit the genetic code. The technology of genetic engineering exemplifies the opportunities and concerns associated with these new abilities. As molecular biologists grow ever more fluent in that language, they are learning to modify an organism's DNA, thus altering life itself.

**We have learned to edit the genetic code.**

Genetic engineering is the process of consciously altering a coded sequence of DNA or RNA. A remarkable variety of enzymes that cut, paste, rearrange, and copy DNA have been discovered; together with sophisticated chemical methods, they comprise a powerful tool kit for the molecular biologist. Any desired sequence of nucleotides can now be synthesized and introduced into cells. Furthermore, with some experimental organisms it is possible to remove specific DNA sequences. The genetic tool kit includes techniques that can be used to compare quickly and accurately DNA from different organisms for screening hereditary diseases, mapping evolutionary pathways, and identifying criminal suspects.

The earliest efforts in genetic engineering, which focused on the large-scale production of proteins for medicine, food production, and basic research, employed single-celled bacteria that reproduce rapidly. Bacterial cells are

exposed to strands of DNA with a desirable gene. Dramatic early success included the development of *E. coli* strains engineered to contain synthetic genes for key components of human insulin and synthetic growth hormone. On a smaller scale, scientists obtain significant quantities of rare proteins by a similar technique. This procedure has proven especially valuable in studies of defective proteins that intentionally incorporate one amino acid mistake.

The protocol for inducing protein synthesis in a bacterial cell, by inserting the appropriate gene into that cell's genome, also works for many plants. Under the proper growth environment, entire plants can be generated from a single cell—an option not yet possible with animals. In one historic series of experiments, plants were infected with engineered bacteria that contained a gene for proteins that are toxic to insects. The bacteria, which attach to wounded plant tissue, insert some of their DNA into the plant cells, causing a tumor to form. Individual plant cells from this tumorous growth developed into a new strain of healthy, insect-resistant plants.

Continuing experiments of this type now focus on increasing crop yields for foods and fiber, extending shelf life of fruits and vegetables, and improving resistance to disease and drought. But new ethical concerns arise from these kinds of genetic engineering. Techniques to insert helpful genes into bacteria might just as easily be used to create highly toxic organisms for use as biological weapons. Also of concern are the unintended consequences of introducing new varieties of life into stable ecosystems.

The engineering of an animal's genome is much more difficult than that of microbes or plants, because we have not yet learned to duplicate animals from the genetic material in a single cell. Some of the difficulties associated with genetic engineering of animals were captured in Michael Crichton's *Jurassic Park*, which dealt with bringing back the dinosaurs.

Crichton's premise is that ancient blood-sucking insects preserve dinosaur blood cells, each with a set of dinosaur DNA. All scientists need to do is collect the preserved insects from amber mines, extract dinosaur cells from their gut, and use the DNA to grow the mighty beasts. Each step in the *Jurassic Park* scenario has a tenuous basis in fact. The most basic problem in bringing an ancient life form back from extinction is obtaining its genome—a

complete set of its chromosomes. In the unlikely event that biochemists obtain a complete set of dinosaur chromosomes, it might be possible to insert the chromosomes into a modern egg. But we do not know how to trigger or sustain its development and growth.

More realistically, these techniques might be the key to preserving, or even increasing, Earth's biodiversity. It might be possible, for example, to obtain an intact genome from a fossil mastodon or mammoth from material frozen in the Siberian wilderness. And libraries of genetic material can be stored for any organism now threatened with extinction.

The most urgent applications of genetic engineering are efforts to find lasting cures for inherited diseases. More than 3,000 inherited human genetic diseases are now recognized. Each of these diseases arises from a different gene defect, and each must be investigated individually. In some instances, a single mistake in a gene's nucleotide sequence leads to a defective protein. In the case of Huntington's disease, the gene defect is related to a variable number of CAG codons, which give long strings of the amino acid glutamine in the corresponding protein.

A new genetic technology may result in routine accurate diagnosis of many types of genetic defects. A glass "chip" is etched with an array of up to 60,000 squares. A different specific nucleotide sequence about 10 bases long is synthesized on each square. A patient's gene, amplified by PCR, binds to the appropriate square when put in contact with the chip. Someday, as the many variants of each gene are understood, this type of DNA analysis may provide everyone with an in-depth genetic medical screening at birth. The challenge, which we shall consider in the next lecture, is how to fix those broken genes. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 24.

## Supplementary Reading

Berg and Singer, *Dealing with Genes*.

Dudley, *Genetic Engineering, Opposing Viewpoints*.

## Questions to Consider

1. What restrictions should the government place on the genetic engineering of microbes? Of plants? Of animals? Of humans?

2. To what extent does a society have the right, or obligation, to determine what constitute undesirable traits (as opposed to undesirable actions)? If an individual repeatedly engages in undesirable actions, does the society have a right, or obligation, to correct undesirable traits that contribute to those actions?

# Cancer and Other Genetic Diseases

## Lecture 53

**[In this lecture], we come to the human genome and its modification. This research is vital, because we've learned a very sobering truth: Cancer and many other diseases are a consequence of errors in our genetic makeup.**

Human ailments are the central focus of today's genetic engineering. Once a genetic disease has been diagnosed by gene typing, we are faced with the questions of how, and whether, the human genome should be altered to correct the disease. Genetic engineering of humans to cure an inherited disease is called gene therapy. In principle, gene therapy accomplishes the same type of genetic changes as in the genetic engineering of microbes or plants. In practice, however, modifying human genes, even for therapeutic purposes, is a daunting challenge, combining scientific hurdles and moral complexities.

The potential of gene therapy is epitomized in the story of Ashanthi DeSilva, who was born in 1986 with a devastating genetic illness, severe combined immunodeficiency. A defect in one critical enzyme, adenosine deaminase (ADA), prevented her immune system from responding to bacterial invaders. Researchers removed some of her blood cells, modified them with a correct version of the gene, and injected the cells back into her body. Six years later, Asha was thriving and living a normal life, her immune system was functioning normally, and doctors were cautiously optimistic that her condition had been cured. For a time it appeared that gene therapy would be the "magic bullet" of the 1990s. But Asha's improvement was not easily explained, and gene therapy remains a hope, not a promise.

Gene therapy through the modification of genetic errors became an exciting, if speculative, area of biomedical research after the first experiments on Ashanthi DeSilva. Since then, more than 100 clinical trials affecting hundreds of patients have begun. While treatment of each disease differs in detail, the basic strategy is the same in every effort: insert a normal gene into genetically defective cells. Several creative strategies have been attempted.

In some instances, defective cells (for example, from the blood or bone marrow) can be removed, modified by inserting the correct segment of DNA or complementary DNA, allowed to multiply, and reintroduced into the body. The most difficult part of this process is insertion of the corrected gene, which must be accomplished by a "vector" that acts as a molecular delivery system. The most common vectors are built from retroviruses—viruses with RNA genomes.

Despite all the hype surrounding gene therapy, not one of the many clinical trials has yielded definitive positive results, and many, such as proposed cures for cystic fibrosis, have been failures. An NIH report in 1995 concluded that gene therapy has not been clinically borne out. Even Ashanthi DeSilva's case is not clear-cut.

Gene therapy on humans affects specific groups of cells in the body; it does not produce genetic alterations that can be inherited. Ultimately, genetic alterations of sex cells may be desirable to eliminate a hereditary disease. Such modifications involve injecting the modified genetic material—a transgene—into an egg. The introduction of transgenic organisms raises serious ethical questions.

Cancer occurs when defects in the genetic machinery cause a cell to divide again and again, in a runaway fashion, forming a tumor. Cancer results from the failure of cells to die. A normal cell ages and dies, while a cancer cell is immortal because its clock is either turned off, constantly reset, or just ignored. Cell death occurs because cells have the ability to recognize and assess damage. The several stopping points along the path to cell division, called checkpoints, serve as essential guardians of life. If the checkpoint machinery spots a defect, then either the defect is repaired, or the cell commits itself to die via programmed cell death. Cancer occurs when the cell cycle continues unchecked, often despite profound damage to the DNA and chromosomes.

Scientists have identified several genes whose protein products affect checkpoint pathways. Mutations in several of these genes appear to be essential for the development of cancer. No single genetic abnormality is sufficient for a normal cell to become a cancer cell; rather, a handful of such

genetic abnormalities is required. Up to ten percent of newly diagnosed cancer patients has inherited an abnormality in one of these genes. Because these individuals already carry what is called the first genetic “hit” on the road to cancer in all of their cells, the probability that any single cell will accumulate the multiple DNA cancer hits needed to make a tumor is much higher than normal. Many of these DNA changes are acquired or accelerated by exposure to chemicals that damage DNA, such as are found in cigarette smoke, organic solvents, pollutants in the environment, and a bad diet.

All aspects of the cell cycle and checkpoint pathways may be affected by defective genes that contribute to cancer development. Some of these genes, called oncogenes, act as accelerators that drive the cycle continuously. In tumor cells, these genes are inappropriately turned on and push the cell through checkpoints that the cell would otherwise not pass. Other genes, called tumor suppressor genes, normally act as brakes that block the progress through cell cycle transitions and respond to damage by turning on either the stop-repair or cell death pathways. The normal functions of these genes are often lost in cancer. A third type of cancer susceptibility gene encodes products directly involved with the DNA repair process or the proteins that participate in programmed cell death.

The recognition of a genetic basis for cancer points to new treatments. But where do we draw the line when it comes to genetic engineering and gene therapy? Few people would balk at saving the life of a child with an incurable genetic disease, but what about lesser ailments, or even behavioral traits? Some day, when we have learned the language of genes and their regulation, humans may gain the ability to design entirely new organisms. It seems inevitable that some day we will be able to modify human traits and abilities. Then the central unanswered question of genetics will be what limits must be placed on its use. The Human Genome Project includes more than $100 million for study of the ethical implications of genetic research—the largest ethics program in human history. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?* Chapter 11.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 25.

## Supplementary Reading

Dudley, *Genetic Engineering, Opposing Viewpoints*.

## Questions to Consider

**1.** Are there any genetic diseases, or predisposition to disease, that run in your family? What progress has been made in identifying the gene or genes responsible?

**2.** Would you use gene therapy to modify the genetic makeup of your child to cure a potentially fatal genetic disease? Would you use gene therapy to increase your child's IQ by 10 points? Would you use gene therapy to change your child's hair color? Where would you draw the line?

# The Chemical Evolution of Life

## Lecture 54

**The question is, How did life arise? For thousands of years, humans have pondered this deep mystery, which lies at the heart of philosophy and religion and, of course, science. The question, in detail, is likely to remain unanswered for many, many decades; but the question is framed by one of the great ideas of biology, that is, that life arose from air, water, and rock, by chemical reactions.**

The long history of life is divided into two parts: chemical evolution of the first living organism, followed by biological evolution. The modern era of origin of life research began in the 1860s with the research of Louis Pasteur (1822–1895), who debunked the prevailing idea of spontaneous generation. Pasteur's dictum of "No life without prior life" pushed back origins to an inconceivably remote time and place.

Is it even appropriate for science to ask the question of life's origins? The origin of life might have been one of the following:

- A miracle—an act of divine intervention.
- An event fully consistent with chemistry and physics but extremely unlikely.
- An inevitable consequence of chemistry, given an appropriate environment and sufficient time.

Only the third option presents the possibility for scientists to study life's origins in the lab through reproducible experiments. The long history of life may be divided into two parts:

- The era of chemical evolution covers the time from the Earth's formation to the appearance of the first living object.

- The era of biological evolution commenced when organisms began to compete with each other for resources.

It's difficult to know what the first life form was like, and it may have been vastly different from anything on Earth today. Like modern life, it must have had three characteristics:

- All life obtains energy and raw materials from its surroundings.

- All life has the ability to grow.

- All life has the ability to reproduce with variations.

The history of origins research places recent studies in context. Two centuries ago, most scientists accepted the idea, championed by Aristotle, of "vitalism." According to this doctrine, a life force permeates the cosmos, and life arises spontaneously all around us, all the time.

French chemist Louis Pasteur (1822–1895) did not accept this idea, and he conducted a series of experiments to show that boiled water could be sterilized. Some of his beakers were sealed; others were contaminated with dust. Pasteur showed that sealed, boiled water remained sterilized indefinitely. Pasteur's ideas led to the development and widespread use of Pasteurization.

Charles Darwin (1809–1882), the British scientist who developed the modern theory of evolution by natural selection, outlined the key requirements for life.

- Life requires water.

- Life requires energy.

- Life requires chemicals—carbon, oxygen, hydrogen, and sulfur, perhaps with nitrogen and phosphorus as well.

Early in the 20th century, several distinguished scientists expanded on these ideas. Most notable among these researchers was the Russian chemist Alekandr Oparin (1894–1980), who proposed the idea that life arose from a body of water that gradually became enriched in organic molecules—the so-called "primordial soup." These ideas are subject to testing in the lab.

Experiments were devised early in the 1950s by University of Chicago chemist Harold Urey and his graduate student Stanley Miller. Miller and Urey started with a sealed flask partially filled with water, to represent the primitive ocean. The rest of the flask was filled with a simple mixture of gases to represent the early atmosphere. While the water was heated, the researchers set off electric sparks in the atmosphere to simulate lightning. At first, the water was clear; but within a couple of days, it became cloudy and then turned shades of brown and pink. When Miller and Urey analyzed the water, they found a complex mixture of organic molecules. Miller's first publication (May 15, 1953, in the journal *Science*) announcing production of amino acids was a bombshell. As exciting and important as these results may be, there is still a major problem: the larger molecules of life tend to break apart, rather than form, under these conditions.

**Life arose from air, water, and rock by chemical reactions.**

Deep hydrothermal zones—especially places on the ocean floor near volcanoes where hot, mineral-laden water flows through cracks in the rocks—are an alternative site for life's origin. There are several good reasons to consider a hydrothermal origin of life. First is a succession of discoveries of deep life:

- The *HMS Challenger* expedition, 1872–1876, discovered many strange new species living in the black depths of the oceans.
- In 1977, Jack Corliss discovered remarkable communities of organisms a mile or more deep on the ocean floor while diving in the submersible Alvin.

Deep ecosystems are dominated by single-celled microscopic organisms at the base of the food chain. These microbes are exceptional for at least three reasons:

- They are largely independent of the surface and the Sun's energy; they obtain their energy by oxidizing the reduced minerals that spew out of the hydrothermal vents, or by reducing the oxidized minerals in the surrounding area.

- Many of these microbes require high pressure to survive.

- Genetic studies show that these microbes are among the most primitive life forms on Earth.

These discoveries prompted Corliss and his co-workers to suggest that submarine hot springs might be the site of life's origin. Subsequent studies have shown that microbes thrive many places underground where there is rock and water. Deep life is sparse, but the volume of Earth's crust is immense. It is thus possible that the mass of these tiny microbes is comparable to that of all the animals and plants we see at the surface.

Other reasons to consider the hydrothermal origins idea come from geology. After the Earth formed 4.5 billion years ago, there were still occasional impacts of remnant planetesimals large enough to blast away the oceans and atmosphere. A hydrothermal origin of life, perhaps deep below the floor of the ocean, might have shielded early life from such insults.

Many planetary scientists are paying special attention to the hydrothermal origins hypothesis. Earth is the only known world with a surface ocean. If life has to arise at the interface between an ocean and atmosphere, then Earth and possibly an early Mars are the only worlds where life could have begun. If life can originate in a deep hydrothermal zone, then several other bodies in our own solar system become good candidates. Of special interest is Jupiter's second moon, Europa, which appears to have a relatively thin ice veneer covering a deep-water ocean.

The hydrothermal origins hypothesis, if it is to survive scientific scrutiny, must eventually be bolstered by chemical synthesis experiments. We are now conducting such experiments in my laboratory at the Carnegie Institution of Washington. Preliminary results show that fast and efficient chemical reactions occur under these conditions. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?* Chapter 8.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 25.

## Supplementary Reading

Deamer and Fleischaker, *Origin of Life*.

DeDuve, *Vital Dust*.

Morowitz, *The Beginnings of Cellular Life*.

## Questions to Consider

1. Consider the possibility that life arose by natural chemical processes and yet was an almost infinitely improbable event. Why would such a scenario preclude a rigorous and conclusive scientific study of life's origins?

2. What observational evidence would convince you that life has originated many times in the universe?

# Biological Evolution—A Unifying Theme of Biology

## Lecture 55

**In this lecture, I examine the subject of biological evolution. First, after reviewing the process of chemical evolution, I want to look at the ongoing conflict between science and religion over evolution, particularly the fundamentalist Christian doctrine of creationism. Then I'm going to outline four compelling bodies of evidence that support the idea that life has changed over time.**

At some point on the ancient Earth, a living organism appeared. That organism may have been the inevitable product of chemical reactions of rock, water, and gas, or life may have begun by a miraculous act. We have abundant observational evidence about life's history since the first living organism appeared about 4 billion years ago. The first living organism found itself in an ocean rich in synthetic nutrients, and with no competition. Life must have spread around the globe quickly. Once life multiplied, it consumed much of the food and began to compete with itself for limited resources. Competition for limited resources leads to change, often with an increase in complexity. The evolution of all life by descent from a common ancestor is a central unifying theme in biology. This idea is at the root of our understanding of the genetic mechanisms, cellular structure, and molecular building blocks that are common to all known life forms.

**Life has changed over more than 3.5 billion years of Earth history.**

Evolution, more than any other great principle of science, has become a lightning rod for attacks from fundamentalist religious groups. The doctrine most at odds with modern scientific theories of evolution is called creationism. Creationism, based on a literal interpretation of versions of the Bible, rests on three precepts: (1) The Earth and the rest of the universe were created relatively recently, perhaps about 10,000 years in the past (2) All life forms were created by God in a miraculous act, more or less in their modern form. (3) The present disrupted surface of the Earth

and the distribution of its fossils are primarily the consequence of one catastrophic flood.

Creationists accept these statements on faith. They are not falsifiable by the scientific method, nor are they subject to modification based on observations of the natural world. All religions have articles of faith, and faith is for many of us an important way of knowing that is different from science. Science and religion need not come into conflict. The scientific principle of gradual evolution, and the vast body of biological and geological evidence that supports it, are seen by many creationists as a challenge to their faith.

Creationists attempt to discredit the theory of evolution on three broad fronts. First, creationists claim that evolution is implausible. It defies the imagination, they say, to think that humans could have evolved by a natural process from one-celled organisms. Second, creationists look for anomalous data in the geological or fossil record. Third, creationists describe evolution as "just a theory," which should be taught side-by-side with creation science, which is also a theory. But U.S. courts have ruled that creationism cannot be taught in a public school science class, because creationism is religion, not science.

Today, virtually all scientists accept evolution as historical fact, based on independently verifiable observations. Numerous lines of evidence point to the common, ancient ancestry of all life. Evidence for evolution comes from comparative anatomy, which was founded by the French naturalist Georges Cuvier (1769–1832). Cuvier focused on the similarities of structure between widely different organisms. The wings of a bat, the flippers of a whale, and the arms of a human are related structural forms, though their functions differ. While Cuvier did not embrace the theory of evolution, subsequent scientists used his methods to trace the evolutionary diversification of life.

Vestigial organs, which are portions of anatomy that are no longer used, provide additional anatomical clues to the evolutionary process. Perfectly adapted organs cannot provide convincing evidence for evolution. Perfection is to be expected if all organisms were created at once in a divine act. However, vestigial organs (e.g., the human appendix and the coccyx bone) have no function and therefore point to gradual change.

The structural unity of life at the microscopic level also points to evolution. All life is made of cells, and all life uses the same molecular building blocks: proteins, lipids, carbohydrates, and nucleic acids.

The study of DNA, the shared genetic material common to all known life, provides compelling evidence for evolution. If life evolved from a single common ancestor, then the DNA of each individual contains a record of evolutionary descent and change. The degree of similarity and difference between the DNA of any two living things, therefore, reflects the time interval to the last common ancestor. A shared genetic mechanism does not prove evolution. It would make sense to use one chemical procedure even if every organism was created independently. As with vestigial organs, one key to seeing evolutionary processes in DNA is to look for unused or superfluous pieces of DNA that have no function. Accumulated errors in DNA also point to evolution.

Molecular phylogeny is the comparative study of certain genes or complex proteins that, in one form or another, are used by all living things. There are many such proteins; about 50% of the proteins in yeast, and 98% of the genes in a chimpanzee, are essentially the same as those found in humans. By comparing degrees of similarity and difference in the details of specific proteins, we can construct an evolutionary tree. An example of this reasoning is provided by a recent computer analysis of 58 manuscript versions of "The Miller's Tale" from Chaucer's *Canterbury Tales*.

Recent studies in molecular phylogeny by Carl Woese of the University of Illinois have focused on proteins in ribosomes—a critical part of the genetic machinery of every cell that turns RNA into proteins. Woese found that the genetic diversity among primitive microbes is vastly greater than that of all multicellular life combined. He also found that many of the microbes that live in extreme environments seem to lie on a separate trunk of this tree of life, close to the hypothetical first common ancestor. Woese has proposed that this group of microbes be named a new kingdom—the Archaea. In this way, molecular phylogeny reveals details of evolution by pointing to living fossils. In the next lecture we shall see that fossils—the record of ancient life in rocks—are the key to understanding evolution. ■

## Essential Reading

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 25.

## Supplementary Reading

National Academy of Sciences, *Evolution and Creationism*.

———, *Teaching About Evolution and the Nature of Science.*

## Questions to Consider

**1.** To what extent should parents be allowed to decide the science curriculum of public schools?

**2.** Investigate some of the beliefs regarding life's origins and evolution from religions beside fundamentalist Christianity.

# The Fact of Evolution—The Fossil Record

## Lecture 56

**I want to tell you about the astonishing fossil record. It spans almost 4 billion years of Earth history. I want to tell you about the nature of fossils. Then I'm going to look at the changing character of life over vast spans of time. Finally, I'm going to look in more detail at the kind of gradual change that life forms show in the fossil record.**

Evolution—the idea that life forms have changed over immense spans of Earth history—is an observational fact as well documented as gravity. A number of theories have been proposed regarding how this process occurs, just as there have been several theories of gravity. But unless our senses lie, life has changed dramatically over time. The primary source of evidence for the evolution of life comes from the rich and varied fossil record.

Fossils are the evidence of ancient life, usually preserved in layers of sedimentary rocks. Most fossils are the preserved hard parts of animals and plants, such as shells, bones, teeth, and wood. Fossils also occur in many other forms, including tracks and trails, casts or impressions, insects preserved in amber, mineralized dung, and leaves in shale. The fossil record refers to all of the varied fossils that have been unearthed in all of the world's rocks. The vast majority of individual organisms, especially those without hard parts, left no trace in the fossil record. The fossil record is thus incomplete. Paleontologists engage in the meticulous process of collecting, studying, and preserving fossils.

**Fossils, the evidence of past life preserved in rocks, record changes of life over Earth's history.**

The most compelling evidence for evolution comes from the broad-brush changes in life on Earth during the past 4 billion years. Earth's history is divided into several long time periods, based on the distinctive characteristics of rocks and fossils from those periods.

Precambrian rocks include all formations more than 543 million years old, before the appearance of animals with shells.

From about 4.5 to 4.0 billion years ago, a period sometimes called the Hadean Eon, the great bombardment slowly subsided. The last great globally sterilizing impact probably occurred toward the end of this period. We do not know when life arose, but the oldest rocks on Earth—formations 3.8 to 3.5 billion years old from Greenland, South Africa, and Australia—contain microscopic fossils of distinctive one-celled organisms.

Rocks from 2.5 to 1 billion years ago reveal an increasing diversity of single-celled and multicellular life. Strands of cells identical to modern blue-green algae suggest the beginnings of an oxygen-rich atmosphere by 2 billion years ago. A number of dramatic changes in life are evident about 1 billion years ago. Worm burrows and the first fossils of jellyfish-like multicellular life are observed. An abundance of soft-bodied, multicellular ocean life appeared world-wide about 600 million years ago, at the end of the Precambrian Period. After the great Precambrian period of life, which spans about 85% of Earth's history, the following periods occurred:

- The Paleozoic Era, from 543 to 248 million years ago, saw a diversification of life and the introduction of many familiar groups of plants and animals. (Everywhere in the world where Paleozoic rocks are found, the same sequence of geological periods and the same distinctive types of fossils are found in the same logical, bottom-to-top sequence. Fossils of a younger period are never found mixed with those of an older period.)

- The "Cambrian explosion" 543 million years ago marks an abrupt and dramatic change in the fossil record. At that point, there appeared the first animals with calcium carbonate shells.

- The Ordovician Period, from 490 to 443 million years ago, was a time of extensive limestone reef formation, with many new forms of marine life.

- The Silurian Period, from 443 to 417 million years ago, was marked by the first land plants, the first insects, and an explosion in varieties of fish.

- During the Devonian Period, from 417 to 354 million years ago, seed plants developed, as did amphibians—the first of the land vertebrates.

- The Carboniferous Period, from 354 to 290 million years ago, saw the first winged insects, the first reptiles, and diverse land plants that formed thick coal deposits.

- The Permian Period, from 290 to 248 million years ago, was marked by the appearance of mammal-like vertebrates and an increasing diversification of land and marine organisms.

- The Mesozoic Era, from 248 to 65 million years ago, began with an unexplained extinction of more than 90% of all species (e.g., trilobites and brachiopods). This mass extinction presented opportunities for new groups of plants and animals.

- The Triassic Period, from 248 to 206 million years ago, saw the appearance of the first true mammals, the first beetles, and the first dinosaurs, which rapidly diversified and became dominant in land, sea, and air environments.

- The Jurassic Period, from 206 to 144 million years ago, was the height of the age of dinosaurs. This era also saw the first birds.

- The first flowering plants evolved during the Cretaceous Period, from 144 to 65 million years ago.

- The Cenozoic Era, from 65 million years ago to the present, began abruptly with the extinction of many groups of animals, including ammonites and the dinosaurs. Geological and geophysical evidence now suggests that a large asteroid hit Earth near the modern-day Yucatan Peninsula, triggering the mass extinction.

- The Tertiary Period, from 65 to 1.8 million years ago, saw the great opportunistic diversification of mammals on land, birds in the air, and bony fishes in the sea. This period also saw an explosion in the varieties and distribution of flowering plants.

- The Quaternary Period, from 1.8 million years ago to the present, is the modern ice age—a time marked by repeated advances and retreats of glaciers. Our genus *Homo* appeared near the beginning of the Quaternary. *Homo sapiens,* or modern man, developed in the last 250,000 years.

The rock record also allows us to observe individual types of organisms over finer time scales. A group of magnificent stalk-eyed trilobite fossils from Ordovician rocks of St. Petersburg, Russia, illustrates this point. The evolution of whales provides a more recent example of the gradual changes documented by the fossil record.

Evolution is a robust theory that makes innumerable predictions about intermediate fossil forms. The fossil record is not complete, but we are constantly filling in the gaps, obtaining an ever more complete picture of life's history of change. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?* Chapter 8.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 25.

## Supplementary Reading

Rudwick, *The Meaning of Fossils*.

## Questions to Consider

1. Can you think of any mechanisms other than superposition by which fossil species could be sorted into distinctive layers?

2. Many scholars prior to the 19th century argued that fossils are not the remains of prior life. What sorts of explanations might they have proposed? (Martin Rudwick's insightful book, *The Meaning of Fossils*, explores this scientific and philosophical issue.)

## The Geological Time Scale

| Era | Period | Epoch | Years Ago (at base) |
|---|---|---|---|
| Cenozoic | Quaternary | *Holocene* | |
| | | *Pleistocene* | 1.8 Million Years Ago |
| | Tertiary | *Pliocene* | |
| | | *Miocene* | |
| | | *Oligocene* | |
| | | *Eocene* | |
| | | *Paleocene* | 65 |
| Mesozoic | Cretaceous | | 144 |
| | Jurassic | | 206 |
| | Triassic | | 248 |
| Paleozoic | Permian | | 294 |
| | Carboniferous | *Pennsylvanian* | |
| | | *Mississipian* | 354 |
| | Devonian | | 417 |
| | Silurian | | 443 |
| | Ordovician | | 490 |
| | Cambrian | | 543 |
| Precambrian | Proterozoic | | 2.5 Billion Years Ago |
| | Archean | | 4.6 Billion Years Ago |

# Charles Darwin and the Theory of Natural Selection

## Lecture 57

**That life has changed over almost 4 billion years of Earth history is as firmly established as any idea in science. But how does life change? More than 150 years ago, the British naturalist Charles Darwin discovered that life on Earth continues to evolve by the process of natural selection.**

Evidence from comparative anatomy, vestigial organs, the structures of cells and molecules, molecular phylogeny, and fossils points to the gradual change of life over time. Our understanding of mechanisms of the evolutionary process is largely the result of the work of the British naturalist Charles Darwin (1809–1882). Darwin, the son of famous parents, was a mediocre student who greatly displeased his father. After abortive studies in medicine and theology, he became interested in natural history, though he was by no means a skilled naturalist when he graduated from Cambridge in 1831. Nevertheless, Darwin was recommended to be the naturalist aboard the *HMS Beagle* on a five-year exploring expedition to South America and the Pacific Islands (1831–1836). Throughout his travels, Darwin noted the large geological effects of gradual change, as well as the variations among species from different regions, most notably subtle differences among species of birds and tortoises from the Galapagos Islands.

At the time of Darwin's travels, it was widely accepted, primarily on religious grounds, that species are unchangeable—the result of a single creation event. Darwin's observations on his voyage caused him to question that idea. By 1837, he had begun a personal "Notebook on the Transmutation of the Species" in which he tabulated evidence for evolution. Having convinced himself of the fact of evolution, Darwin set about trying to understand the mechanism of evolution. He was influenced by British economist Thomas Robert Malthus (1766–1834), whose *Essay on the Principle of Population* (1798) explored the relationship between food supply and human population. Darwin saw a parallel to animal and plant populations in the natural world. By 1842, he had written a brief outline of a new theory

of evolution and shared it with a few colleagues. He hesitated to publish the work, however, knowing the great resistance his ideas would meet.

In 1858, after considerable prodding from his friends and a letter from the naturalist Alfred Russell Wallace, who had independently arrived at a similar theory, Darwin wrote an "abstract" of his thesis—the revolutionary book *The Origin of Species,* which was published in 1859. Darwin's *The Origin of Species* describes the process of evolution by natural selection. The theory is based on a few simple observations:

- All species produce more offspring than can possibly survive to maturity, because resources of food, water, and space are limited.

- Individuals of a species display variations in physical characteristics. An individual's traits, furthermore, usually resemble those of its parents.

- Advantageous traits provide an individual with a better chance of surviving to produce more offspring, passing those traits from one generation to the next.

- After many generations, gradual changes add up to large changes—evolution.

Darwin labeled this process natural selection. He drew parallels with the process of artificial selection, or selective breeding, well known to his British audience. Recent work on the evolution of eyes by theoretical biologists Dan Nilsson and Susanne Pelger of Lund University in Sweden illustrates Darwin's ideas.

Darwin's *The Origin of Species* created much controversy. Many theologians denounced the work for its blatant contradiction of the scriptural view that all life forms were created by God. Many found Darwin's ideas distasteful because the struggle for survival implied an amoral natural world. Others embraced Darwin's ideas but used them to support social stratification—an extreme the author never intended.

Darwin and his colleagues were troubled by the lack of known physical mechanism for change. The genetic research of Gregor Mendel, and subsequent discoveries of DNA and the genetic code, have now filled in that gap. The merging of genetic material from two parents during sexual reproduction explains the origin of variation in offspring, as well as the similarities of offspring to parents. Random genetic mutations may represent an additional mode of variation.

**Life on Earth continues to evolve by the process of natural selection.**

Darwin's original thesis is that change in species occurs slowly, in small increments. The fossil record does not always conform to this idea. In 1972, American paleontologists Stephen Jay Gould and Niles Eldridge challenged conventional wisdom with an opposing viewpoint called punctuated equilibrium, which claims that species change one to another in relatively sudden bursts, without a leisurely transition period. These episodes of rapid speciation are separated by relatively long static spans during which a species may change hardly at all. The punctuated equilibrium hypothesis attempts to explain a curious feature of the fossil record—that many distinctive fossil species appear to remain unchanged for millions of years. The evolution of North American horses, which was once presented as a classic textbook and museum example of gradual evolution, is now providing equally compelling evidence for punctuated equilibrium.

One of the key ideas of Darwin's theory of evolution by natural selection is that new species arise to replace old species. The disappearance of a species is called extinction. One of the hottest topics of current evolutionary research has to do with the rate of extinction. The extinction rate is not constant. In some formations, millions of years of sediments may contain an almost constant assemblage of organisms. Other strata show abrupt loss of many species. The fossil record reveals a half dozen "mass extinctions," in which a significant fraction of all species became extinct in a geological instant. At least five major extinction episodes and perhaps a dozen more lesser ones reveal that life on Earth is both vulnerable and resilient.

The causes of mass extinctions are a matter of debate. One clear contributing cause has been death by large asteroid impacts. World-wide evidence now suggests that the dinosaurs suffered such a fate 65 million years ago when an asteroid slammed into the Yucatan Peninsula. Reasons for the great Permian extinction 245 million years ago are not known, though some scientists point to rapid climate change as the culprit.

Of all historic extinction events, the disappearance of most large North American mammals, including mastodons, mammoths, and woolly rhinoceros, about 11,000 years ago is perhaps most sobering. Fossil bones indicate that approximately two-thirds of large mammal species in North and South America died out about that time. This mass extinction differs from others in two key respects: smaller life forms do not appear to have been affected, and human stone weapons are found among the scavenged bones. Thus, to the list of potential causes of mass extinction, we must add human activities. There is evidence that we are now in a period of massive extinction, due largely to the effects of human activity. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?* Chapter 10.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 25.

## Supplementary Reading

Darwin, *The Origin of Species*.

Gould, *The Panda's Thumb*.

National Academy of Sciences, *Teaching About Evolution and the Nature of Science*.

Weiner, *The Beak of the Finch*.

## Questions to Consider

1. Is evolution taught in the science curriculum of your local public high school?

2. What alternative explanations, besides human activities, might explain the recent mass extinction of large mammals?

# Ecosystems and the Law of Unintended Consequences
## Lecture 58

**One of the great principles of biology is that all individuals are part of ecosystems, which are complex communities of organisms and their physical environment.**

Species never occur in isolation; they always occur as part of an ecosystem. All ecosystems are dependent on both living and nonliving parts. The physical and chemical environment, including weather and climate, the nature of local rocks and soils, and the temperature and salinity of local bodies of water, defines the nonliving portions. All species that interact in an ecosystem form ecological communities, which always include a host of microbes.

All ecosystems require energy, which flows through an ecosystem according to the laws of thermodynamics. The flow of energy through an ecosystem is called the food web. Every organism must obtain energy, either from its environment or by eating other organisms. The concept of trophic levels defines a hierarchy of energy producers and consumers in an ecosystem. At each trophic level, most of the available energy is unused. The ratio of biomass of plants to herbivores to carnivores is typically 100:10:1. Large carnivores are relatively rare.

Every organism in an ecosystem occupies an ecological niche, and each niche represents a specific strategy for obtaining energy and atoms from the environment. Every organism must compete for resources in its ecological niche. An ecosystem does not usually support two species in identical ecological niches. However, populations of different species achieve a balance in stable ecosystems. A change in environment or the introduction or loss of a species can disrupt an ecosystem. The disruption can be gradual, as in a climate change, or it can be sudden and dramatic.

Rapid and unexpected changes in ecosystems have led environmentalists to an important insight about complex systems—the Law of Unintended Consequences, which states that any change in one part of a complex system

may affect other parts of the system, in ways that are often unpredictable. One surprising example is provided by the story of the near-extinction of the Peter's Mountain Mallow, a small flowering plant that had steadily declined until there were only 4 surviving plants.

The lives of millions of people who live near the shores of Lake Victoria, the largest fresh water lake in Africa, were affected by an unintended consequence of one species change. For centuries, these people relied on tilapia and other small fish as a major source of protein. In the 1960s, the large predatory Nile perch was introduced into the lake in an effort to attract more sport fishermen to the area as tourists. The perch thrived with no natural enemies and vast supplies of the smaller fish, while the population of other fish plunged. These smaller fish had controlled populations of surface algae; soon, algae spread over parts of the lake surface, and dead algae sank, decaying and consuming oxygen in depths where other fish used to live. The tilapia also had controlled the population of snails, which carry human parasites; the incidence of parasitic disease increased accordingly. Native fishermen now catch the Nile perch, but these large fish must be dried over a fire, rather than sun-dried. As a result, forests have been stripped from the lake's shoreline, causing extensive soil erosion into the lake and further disruption of the ecosystem.

**All ecosystems require energy, which flows through an ecosystem according to the laws of thermodynamics.**

In many cases, causes of population change are not nearly so obvious. In the 1980s, naturalists began to notice that frog populations around the world had been declining. Some ecologists view the change with a sense of foreboding. They tend to think of the environment as a fragile thing under assault by opportunistic industry, uncaring governments, and an exploding world population. Others, believing the environment to be resilient and human needs of first priority, take a more optimistic position.

Humans do change ecosystems. What concerns many scientists is that we can't predict how. As the human population grows, we alter the balance of matter and energy in several ways:

- We command an ever larger share of water and nutrients—resources essential to all living things.

- Habitats are eliminated through deforestation, farming, urbanization, and other endeavors.

- Humans also affect environments by eliminating species.

- Human activities result in a wide variety of air, water, and soil pollution, which may degrade ecosystems on a regional or global scale.

One hope for understanding the behavior of ecosystems is experimental field work. One experimental strategy is altering one variable of a complex system at a time. This approach pervades modern biological research, from genetics to brain science. Unfortunately, ecosystems are not that simple; all of the components are complexly interconnected. An alternative research approach is to model ecosystems by computer.

Three reasons have been cited for preserving Earth's biodiversity:

- All species are interdependent on others as part of complex ecosystems. Loss of one species may adversely affect the whole system with consequences that are unexpected and unpredictable.

- Humans have enjoyed untold benefits from the new foods, new drugs, and new chemicals discovered among living things. Countless natural substances, many of them of great economic value, surely remain to be discovered. Each lost species may thus be mourned as a lost opportunity for improving our lot.

- Many argue for species protection on ethical and aesthetic grounds. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?* Chapter 7.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 19.

## Supplementary Reading

Ward, *The End of Evolution*.

## Questions to Consider

1. Identify an environmental concern in your community. What are the pros and cons of the proposed solution?

2. Should citizens of the United States be concerned about the extinction of species in South America? How might we influence the preservation of such species?

# The Ozone Hole, Acid Rain, and the Greenhouse Effect

## Lecture 59



**I want to focus on three great modern problems that are affecting human society. The first of these is the ozone hole; the second, acid rain; and third, the greenhouse effect. In each of these stories, I'm going to focus on both what we know and what we don't know, and also some of the possible solutions to these great problems.**

Stories about the environment and global climate change are often in the news. These stories are frequently based on new scientific measurements and observations yet have a decidedly political tone. Some observers tend to think of the environment as a fragile thing under assault by opportunistic industry, uncaring governments, and an exploding world population. Others, believing the environment to be resilient and human needs of first priority, take the more optimistic position that the Earth can take care of itself.

The most pressing unanswered questions about the environment relate to specific human actions and their consequences. It's easy to deal with localized, short-term problems. For example, authorities waste no time in treating a toxic chemical spill. As problems become more gradual and less localized, the details of cause-and-effect relationships become increasingly fuzzy.

A half century from now, the salvation of the Earth's ozone layer may be viewed as one of the great environmental triumphs of our time. The ozone layer is a region of the stratosphere, about 35 km up, that has a small but significant amount of the molecule ozone, $O_3$. Ozone absorbs the Sun's harmful UVB ultraviolet radiation, which can severely affect plant growth and is a major factor in human skin cancer. The ozone layer thus serves as an essential shield for life at the Earth's surface.

In the 1950s, gases called chlorofluorocarbons (CFCs) were found to provide cheap and nontoxic materials for refrigerants and other applications. Production of freon and other CFCs quickly grew into a major chemical

industry. Doubts about the safety of CFCs were first raised in the 1970s, following a series of chemical experiments on ozone. In 1970, Dutch chemist Paul Crutzen demonstrated that ozone can be depleted by chemical reactions with nitrogen oxides, a common ingredient of smog. A few years later, Americans Mario Molina of MIT and F. Sherwood Roland of the University of California at Irvine added to concerns with their discovery that CFCs can release chlorine and cause the rapid destruction of ozone through a series of simple chemical reactions.

In 1985, a British scientific survey revealed severe depletion of ozone over Antarctica. The region over the Antarctic with reduced ozone is called the ozone hole. The ozone hole appears for a few months during the Southern Hemisphere's spring. Since 1985, the ozone hole has gotten steadily larger, deeper, and longer in duration. In response to the growing danger, seventy nations signed the 1987 Montreal Protocol, a treaty to eliminate the production of CFCs by the year 2000.

Burning, the chemical reaction of oxidation, inevitably introduces gaseous molecules into the atmosphere. Carbon dioxide and water vapor are always produced, because fossil fuels are primarily compounds of carbon and hydrogen. But fossil fuels always have small amounts of the elements sulfur and nitrogen, and these elements form oxide compounds that contribute to the formation of acid rain.

Nitrogen oxides form by the chemical reaction of nitrogen ($N_2$) and oxygen ($O_2$) molecules whenever air is heated to above 500°C. Several different nitrogen oxide, or $NO_2$, compounds are produced; in the atmosphere, nitrogen oxides react with water molecules to form molecules of nitric acid, $HNO_3$. Similarly, sulfur in fossil fuels oxidizes when burned to form sulfur dioxide, $SO_2$. In the atmosphere, sulfur dioxide combines with water molecules to form molecules of sulfuric acid, $H_2SO_4$. Most of these harmful sulfur and nitrogen emissions come from power plants and factories that burn dirty fossil fuels, as well as automobile emissions.

Raindrops collect these acid molecules and so become acid rain. Acid rain causes rapid dissolution of limestone and other soft sedimentary building stones. When acid rain falls in high mountainous areas, lakes,

ponds, and groundwater may become extremely acidic, dramatically altering ecosystems.

The political difficulty in dealing with acid rain is that the sources of the nitrogen and sulfur oxides are far from the sites where the acid rain falls. The solutions to acid rain are straightforward but quite expensive. These modifications will cost consumers money. Factory jobs also may be lost to countries with less stringent pollution requirements.

Increased concentrations in carbon dioxide and a few other atmospheric gases may contribute to a greenhouse effect, thereby increasing global temperatures. The greenhouse effect is the tendency of some atmospheric gases to transmit visible and UV wavelengths but absorb infrared wavelengths, like the glass of a greenhouse. Thus, the Sun warms the Earth, and that heat is trapped. The greenhouse effect is essential to the survival of life on Earth. Without the trapped heat, Earth would freeze over. Too much global warming, however, could cause melting of polar ice and a substantial rise in ocean levels, as well as shifts in global climate.

Global warming research advances on many fronts. The most basic data are ongoing measurements of global ocean and atmospheric temperatures. Historically, most temperature measurements have been made in urban areas—regions that have experienced significant warming over the past century simply due to the increased area of pavement. Detailed annual measurements of temperature in rural areas, on mountaintops, and over the ocean provide a better picture. They suggest that a small but statistically significant increase of about one-half degree Celsius has occurred during the past half century. A global network of microwave-sensing satellites also has detected slight global warming over the past decade. An international gathering of one thousand experts endorsed the conclusion that warming is occurring, in a 1995 report of the United Nations' Intergovernmental Panel on Climate Change.

The other half of the global warming cause-and-effect equation is carbon dioxide. Carbon dioxide is only one of several greenhouse gases, and not the most important one. Water vapor and methane ($CH_4$) are more important, but carbon dioxide appears to be the gas subject to the greatest variation in

concentration. $CO_2$ concentrations have increased by as much as 15% in the last forty years alone, presumably due to increased burning of fossil fuels.

These two facts—that the atmospheric concentration of carbon dioxide is increasing and that the Earth appears to be getting warmer—are not necessarily cause and effect. The slight rise in temperature might be due to increased solar energy output, which fluctuates in as yet poorly understood ways. It is essential to document details of the complex global cycles of carbon and oxygen.

**Human activities can affect the global environment, often in ways that are difficult to predict.**

From the political point of view, two questions rise above all others. First, are increased $CO_2$ concentrations leading to an increase in global temperatures? Global circulation computer models invariably predict warming associated with increased atmospheric carbon dioxide. Cloud cover, which cools the Earth, is a major uncertainty. Other factors include vegetation, rate of polar ice melting, carbon dioxide uptake by the oceans, and the mitigating effects of sulfates and other aerosols—but every model predicts warming.

The second question is, how much will it cost in social and economic terms to wean ourselves from fossil fuels? Any effort to reduce drastically the consumption of fossil fuels will cost consumers money and might require significant changes in lifestyles. Some politicians from regions rich in fossil fuels, or those dependent on their use, discount the significance of the greenhouse effect.

We don't know the percent of ozone loss that is due to CFCs, but we know it's not trivial. We don't know how much global warming will take place during the next half century, but all models indicate it is taking place. We can't predict the consequences of widespread species loss and elimination of rain forest ecosystems, but we do know such loss is irreversible.

In the face of such environmental projections, supported by the preponderance of evidence and endorsed by the vast majority of experts working in the field,

it's only common sense to protect the environment. If we conserve, then the worst that can happen is that we consume a little less today and pass the Earth's resources on as a legacy to future generations, who may be better able to predict the consequences of their actions. Scientific research on the environment is essential to address the magnitude of the problem.

The most troubling unanswered questions about the human population explosion and environmental change lie outside the domain of science. When we reach the inevitable realization that the human population has grown too large, what do we do? ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?* Chapter 7.

Trefil and Hazen, *The Sciences: An Integrated Approach*, Chapter 19.

## Supplementary Reading

Benedick, *Ozone Diplomacy*.

Michaels, *The Sound and the Fury: The Science and Politics of Global Warming*.

## Questions to Consider

1. What automobile emission regulations are in effect in your area? Which gaseous molecules are monitored, and what are the acceptable levels of those pollutants?

2. How much would you be willing to change your lifestyle in order to ensure a sustainable environment for your grandchildren?

# Science, the Endless Frontier

## Lecture 60

**Rather than capping off with one more of the great discoveries of science, I want to explore some of the unanswered questions of science, the vast scientific frontier that remains unexplored.**

Recently, a number of science watchers have claimed that science is approaching its end—that all there is of significance to be learned about the natural world will be learned. For example, science journalist John Horgan has recently claimed that the end of science is at hand. Supposedly, we are nearing the time when all the great laws of nature will have been deduced. The gist of Horgan's claim is that there are only so many things to know about the universe. Each discovery brings us closer to knowing everything. This point of view ignores the nature of the scientific process and the character of the questions it attempts to answer. Countless profound, deeply fascinating questions await scientists of this and future generations.

William Harvey, the 17th-century English physician who discovered the nature of blood's circulation, spoke for today's researchers when he said, "All that we know is still infinitely less than all that remains unknown." The key to understanding why science is an endless frontier lies not in cataloging what we know, but rather in recognizing the vast amount of what remains unknown.

A recent survey of scientists in many fields identified a few big, unanswered questions.

- The largest group placed questions about the mind, the brain, and the nature of consciousness near the top of their list.

- Physical scientists count scientific mysteries about the nature of gravity and the nature of time high on their list.

- Social scientists raise big questions about the inevitability of war, the rules of economics, and the best way to raise a child.

- Then there are the pressing questions related to human needs: increasing food production, understanding Earth's global climate, and curing disease.

One of the greatest mysteries of life resides in the fertilized egg, the microscopic object from which everyone develops. From a single cell arises a wide variety of specialized structures composed of many different kinds of cells. As the first cell divides again and again, primitive structures appear. Head, gut, legs, and heart take on their unique identities, while new generations of cells play the specialized roles of blood, bone, and brain. How does it happen?

Perhaps no other question in science could have a more complex and lengthy complete answer. To document and describe the countless individual steps that yield a single fly would require thousands of thick volumes. For a human being, the volumes might number in the millions.

Developmental biology is a peculiar sort of science. It's almost impossible to track the genetic pathways of development when everything goes right. For this reason, developmental biologists concentrate their efforts on much simpler fast-breeding organisms in which something goes very wrong. Developmental biologists subject flies to radiation or chemicals to make mutants. Bizarre mutant flies with extra eyes, deformed wings, or legs sticking out of their heads provide an intellectual gold mine for these researchers who match these deformities with mutated genes.

The chemical signals that control development begin in the egg. In flatworms, the egg's first cell division always results in a larger cell to the front and a smaller cell to the rear. The egg can't control development forever. In the flatworm, after two cell divisions (four cells total), removal of any one cell will result in grievous deformity. Each cell's role is determined by which of its genes turns on and which turns off. One set of switches produces a nerve cell, while another set generates muscle or skin. Every step is controlled by chemical signals—a unique chemical mix in a unique three-dimensional

configuration. We may never know all the details of the developmental processes. What we can hope to learn, perhaps within a few decades, are the general principles that govern the development, life, and eventual death of all living things.

"Are we alone?" remains one of the most profound unanswered questions. The search for extraterrestrial intelligence is called SETI. Prior to the late 1950s, before the launch of Sputnik, any quest for alien life was mocked as beyond the domain of serious science. In 1959, Giuseppe Cocconi and Philip Morrison, both physicists at Cornell University, transformed the scientific status of SETI by proposing a simple and compelling experimental search strategy. They proposed looking for characteristic radio signals from nearby Sun-like stars. They based their argument on the intriguing possibility that a scientifically advanced alien society might have established a radio signal beacon in the hopes of attracting our attention.

**No one can predict what we don't know we don't know.**

"Are we alone?" is a question unlike most others in science. Most scientific questions are answered only gradually and require lengthy and inherently incomplete answers. The search for other intelligent, technological life forms differs. The only possible answers are: "Yes, we are" or "We don't know." A single, unambiguous communication or direct contact with another technological species would instantly answer the question and change forever our perception of life in the universe. The question also differs from most others in science in that it may be answered even if we never lift a finger to study it. They may find us first. Of course, if alien life is found, myriad new questions about their distant origins, novel biology, technological capabilities, and ultimate intentions will arise.

Although we know of no alien technological societies, we can attempt to guess the probability of their existence. SETI pioneer Frank Drake, Professor of Astronomy at the San Diego campus of the University of California, suggested that seven factors, each worthy of independent thought and study, contribute to the probability that intelligent life exists on other worlds.

- How many stars are Sun-like? Drake estimated that our galaxy holds perhaps half a billion possible suns.

- How many Sun-like stars have solar systems? In our present view of star formation from a nebula of dust and gas, planetary systems are almost inevitable.

- How many solar systems have Earth-like planets? The hallmark of Earth is the abundance of liquid water, which is stable in a relatively narrow temperature range. Nevertheless, the number of Earth-like planets orbiting Sun-like stars in our galaxy may be in the hundreds of millions.

- What fraction of Earth-like planets have life?

- How often does life lead to intelligence?

- Will intelligent life forms attempt to communicate?

- How long do advanced societies remain communicative?

What is the solution to the Drake equation? By his most optimistic estimate, assuming that almost every Earth-like planet eventually develops intelligent life, Drake suggested that signals will originate from one in every four potential planets—perhaps 150 million in all. His most pessimistic calculation assumes signals are broadcast from one in a million Earth-like planets—perhaps only 500 in the entire galaxy.

Astronomer Carl Sagan favored an intermediate number of as many as 10 million technological communities. If so, then the chances are good that one of them lives within 100 light years of our solar system. Our radio waves, first broadcast commercially early in the 20th century, may have already begun to bathe that distant planet. And our closest stellar neighbors may have already formulated a reply.

The central problem confronting SETI scientists is where and how to search for such a signal. Three radio broadcast variables must be matched: direction

to the source, frequency of the signal (as modified by red or blue shifts), and sensitivity (the intensity of the source above background noise). The staggering number of possible combinations of these conditions makes the SETI effort something akin to searching for a needle in a cosmic haystack. SETI scientists suspect that a communication from an intelligent species will be unambiguous. Perhaps it will begin with a sequence representing the prime numbers: 1, 2, 3, 5, 7, 11, and 13 short pulses repeated over and over again to get our attention. Then a binary-coded message of dots and dashes could convey basic information about the senders and their world. NASA discontinued its funding for SETI research in the early 1990s, but a number of SETI research projects are now sponsored by private groups such as the Planetary Society.

Even a cursory review of today's most compelling scientific questions promises centuries of research adventure and discovery. We can imagine no end to the questions. ■

## Essential Reading

Hazen and Singer, *Why Aren't Black Holes Black?*

## Supplementary Reading

Horgan, *The End of Science*.

Lawrence, *The Making of a Fly*.

Sullivan, *We Are Not Alone*.

## Questions to Consider

**1.** Identify a few of the things that you know you don't know. Which of them are impossible to answer?

**2.** During this lecture series, what are some of the ideas you learned that you didn't know you didn't know?

# Concordance to the Science Content Standards of the *National Science Education Standards*

The *National Science Education Standards* (National Academy of Sciences, 1997) represents a consensus among thousands of scientists and educators, regarding the most effective approaches for teaching and learning about science. The *Standards* provide American parents, teachers, and school administrators with an unprecedented building code for developing effective science curricula. The *Standards* focus on several aspects of science education, including classroom methods, assessment, teacher preparation, and science content standards.

This 60-lecture course has been designed to introduce and review all of the scientific principles that are included in the K–12 "Content Standards" portions of the *National Science Education Standards*. All content standards in physical, earth, space, and life sciences are covered, as are aspects of the nature of science, the history of science, science and technology, and science in personal and social perspectives.

For the convenience of curriculum developers, the following outline matches all *National Science Education Standards* content standards to specific lectures (numbered 1 to 60).

**I.** Unifying Concepts and Processes, K–12

- **A.** Systems, order, and organization (all lectures, especially 1–4)
- **B.** Evidence, models, and explanation (all lectures, especially 1–4)
- **C.** Constancy, change, and measurement (1, 3, 35–42, 54–58)
- **D.** Evolution and equilibrium (35–36, 44, 54–57)
- **E.** Form and function (22–26, 43–47)

**II.** Content Standards, K–4

- **A.** Science as Inquiry (1–2, 60)
- **B.** Physical Science:
    - **1.** Properties of objects and materials (22–26)

2. Position and motion of objects (3–6)
3. Light, heat, electricity, and magnetism (11–16)

C. Life Science:
1. Characteristics of organisms (43–44)
2. Life cycles of organisms (44, 60)
3. Organisms and environments (58–59)

D. Earth and Space Science:
1. Properties of earth materials (39–42)
2. Objects in the sky (3–4, 29–31)
3. Changes in earth and sky (3–4, 29–32)

E. Science and Technology:
1. Abilities of technological design (many lectures, especially 52–53)
2. Understanding about science and technology (examples throughout)

F. Science in Personal and Social Perspectives:
1. Personal health (15, 45–46, 58–59)
2. Characteristics and changes in populations (58)
3. Types of resources (42)
4. Changes in environments (40–41, 58–59)
5. Science and technology in local challenges (throughout, especially 59)

G. History and Nature of Science: Science as a human endeavor (throughout)

**III.** Content Standards: 5–8

A. Science as Inquiry (throughout, especially 1–2, 60)

B. Physical Science:
1. Properties and changes of properties in matter (22–28)
2. Motions and forces (4–6, 11)
3. Transfer of energy (7–8, 21, 28)

C. Life Science:
1. Structure and function in living systems (43–47)
2. Reproduction and heredity (48–51)
3. Regulation and behavior (44, 60)
4. Populations and ecosystems (58–59)

5. Diversity and adaptations of organisms (44, 57–59)

**D.** Earth and Space Science:
1. Structure of the earth system (36–39)
2. Earth's history (35–39, 42)
3. Earth in the solar system (34–36)

**E.** Science and Technology (throughout, especially 26, 28)

**F.** Science in Personal and Social Perspectives:
1. Personal health (15, 27)
2. Populations, resources, and environments (40–42, 58–59)
3. Natural hazards (37–39, 41)
4. Risks and benefits (15, 28, 58–59)
5. Science and technology in society (22, 26, 28, 52–53, 57–59)

**G.** History and Nature of Science:
1. Science as a human endeavor (1–3, 60, and throughout)
2. Nature of science (1–2, 33, 60, and throughout)
3. History of science (examples used throughout)

**IV.** Content Standards: 9–12

**A.** Science as Inquiry (1–2, 60, and throughout)

**B.** Physical Science:
1. Atoms (17–20, 27)
2. Structure and properties of matter (17–18, 21–26, 33)
3. Chemical reactions (21, 24)
4. Motions and forces (3–6)
5. Conservation of energy and increases in disorder (8–10)
6. Interactions of energy and matter (14–16, 24, 28, 33)

**C.** Life Science:
1. Cells (47, 49)
2. Molecular basis of heredity (49–52)
3. Biological evolution (54–57)
4. Interdependence of organisms (43–44, 58–59)
5. Matter, energy, and organization in living systems (10, 12, 43–47, 58)
6. Behavior of organisms (43–44)

**D.** Earth and Space Science:
1. Energy in earth systems (28, 30, 36, 38–39)

2. Geochemical cycles (40–42)
3. Origin and evolution of the earth system (34–36, 42)
4. Origin and evolution of the universe (31–32)

**E.** Science and Technology:

1. Technological design (26, 28, 52)
2. Understanding about science and technology (28, examples throughout)

**F.** Science in Personal and Social Perspectives:

1. Personal and community health (27, 45–46, 53, 59)
2. Population growth (40, 58–59)
3. Natural resources (40–42)
4. Environmental quality (40–41, 58–59)
5. Natural and human-induced hazards (28, 39, 41)
6. Science and technology in local, national, and global challenges (27–28, 58–59)

**G.** History and Nature of Science:

1. Science as a human endeavor (1–4, 33, 60)
2. Nature of scientific knowledge (1–2, 60)
3. Historical perspectives (examples used throughout)

# The Periodic Table of the Elements

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogen *** H 1.008 1 | | | | | | | | | | | | | | | | | Helium *** He 4.003 2 |
| Lithium * Li 6.941 3 | Beryllium * Be 9.012 4 | | | | | | | | | | | Boron * B 10.81 5 | Carbon * C 12.01 6 | Nitrogen *** N 14.01 7 | Oxygen *** O 16.00 8 | Fluorine *** F 19.00 9 | Neon *** Ne 20.18 10 |
| Sodium * Na 22.99 11 | Magnesium * Mg 24.31 12 | | | | | | | | | | | Aluminium * Al 26.98 13 | Silicon * Si 28.09 14 | Phosphorus * P 30.97 15 | Sulfur * S 32.07 16 | Chlorine *** Cl 35.45 17 | Argon *** Ar 39.95 18 |
| Potassium * K 39.10 19 | Calcium * Ca 40.08 20 | Scandium * Sc 44.96 21 | Titanium * Ti 47.87 22 | Vanadium * V 50.94 23 | Chromium * Cr 52.00 24 | Manganese * Mn 54.94 25 | Iron * Fe 55.84 26 | Cobalt * Co 58.93 27 | Nickel * Ni 58.69 28 | Copper * Cu 63.55 29 | Zinc * Zn 65.39 30 | Gallium * Ga 69.72 31 | Germanium * Ge 72.63 32 | Arsenic * As 74.92 33 | Selenium * Se 78.96 34 | Bromine ** Br 79.90 35 | Krypton *** Kr 83.80 36 |
| Rubidium * Rb 85.47 37 | Strontium * Sr 87.62 38 | Yttrium * Y 88.91 39 | Zirconium * Zr 91.22 40 | Niobium * Nb 92.91 41 | Molybdenum * Mo 95.94 42 | Technetium * Tc [98] 43 | Ruthenium * Ru 101.07 44 | Rhodium * Rh 102.91 45 | Palladium * Pd 106.42 46 | Silver * Ag 107.87 47 | Cadmium * Cd 112.41 48 | Indium * In 114.82 49 | Tin * Sn 118.71 50 | Antimony * Sb 121.76 51 | Tellurium * Te 127.60 52 | Iodine * I 126.90 53 | Xenon *** Xe 131.29 54 |
| Caesium * Cs 132.91 55 | Barium * Ba 137.33 56 | LANTHANIDES | Hafnium * Hf 178.49 72 | Tantalum * Ta 180.95 73 | Tungsten * W 183.84 74 | Rhenium * Re 186.21 75 | Osmium * Os 190.23 76 | Iridium * Ir 192.22 77 | Platinum * Pt 195.08 78 | Gold * Au 196.97 79 | Mercury ** Hg 200.59 80 | Thallium * Tl 204.38 81 | Lead * Pb 207.2 82 | Bismuth * Bi 208.98 83 | Polonium * Po [209] 84 | Astatine * At [210] 85 | Radon *** Rn [222] 86 |
| Francium * Fr [223] 87 | Radium * Ra [226] 88 | ACTINIDES | Rutherfordium **** Rf [267] 104 | Dubnium **** Db [268] 105 | Seaborgium **** Sg [269] 106 | Bohrium **** Bh [270] 107 | Hassium **** Hs [269] 108 | Meitnerium **** Mt [278] 109 | Darmstadtium **** Ds [281] 110 | Roentgenium **** Rg [281] 111 | Copernicium **** Cn [285] 112 | Ununtrium **** Uut [286] 113 | Flerovium **** Fl [289] 114 | Ununpentium **** Uup [289] 115 | Livermorium **** Lv [293] 116 | Ununseptium **** Uus [294] 117 | Ununoctium **** Uuo [294] 118 |
| | | | | | | | | | | | | | | | | | |
| | | Lanthanum * La 138.91 57 | Cerium * Ce 140.12 58 | Praseodymium * Pr 140.91 59 | Neodymium * Nd 144.24 60 | Promethium * Pm [145] 61 | Samarium * Sm 150.36 62 | Europium * Eu 151.96 63 | Gadolinium * Gd 157.25 64 | Terbium * Tb 158.93 65 | Dysprosium * Dy 162.50 66 | Holmium * Ho 164.93 67 | Erbium * Er 167.26 68 | Thulium * Tm 168.93 69 | Ytterbium * Yb 173.04 70 | Lutetium * Lu 174.97 71 | |
| | | Actinium * Ac [227] 89 | Thorium * Th 232.04 90 | Protactinium * Pa 231.04 91 | Uranium * U 238.03 92 | Neptunium * Np [237] 93 | Plutonium * Pu [244] 94 | Americium * Am [243] 95 | Curium * Cm [247] 96 | Berkelium * Bk [247] 97 | Californium * Cf [251] 98 | Einsteinium * Es [252] 99 | Fermium * Fm [257] 100 | Mendelevium * Md [258] 101 | Nobelium * No [259] 102 | Lawrencium * Lr [262] 103 | |

# Timeline

| | |
|---|---|
| c.3000 B.C. | Builders of ancient monuments, such as Stonehenge in England, recognize reproducible events in the heavens. |
| c.430 B.C. | Democritus of Abdera advocates the atomic theory of matter on philosophical grounds. |
| c.370–330 B.C. | Aristotle’s teaching and writings on astronomy, physics, and biology exert a great influence on subsequent scholars. |
| c.50–59 | Pliny the Elder catalogs thousands of “facts” in his 37-volume *Natural History.* |
| c.145 | Ptolemy of Alexandria proposes an Earth-centered model of the solar system that incorporates epicycles. |
| 1543 | Copernicus publishes Sun-centered model of the solar system, and Vesalius publishes his study of human anatomy. |
| 1572 | Tycho Brahe discovers a new star—a supernova in the constellation Cassiopeia. |
| 1581 | British instrument maker Robert Norman publishes *The Newe Attractive*, in which he describes magnetic dip. |
| 1600 | English physician William Gilbert publishes *De Magnete*. |
| 1600 | Johannes Kepler becomes Tycho Brahe’s assistant. |

1609 ............................................. Galileo Galilei builds his first telescopes. His first observations were published in *The Starry Messenger* in 1610.

1619 ............................................. Kepler publishes *Harmony of the World*, which introduces his third law of planetary motion.

1632 ............................................. Galileo publishes *Dialogue Concerning Two World Systems*, which led to his heresy trial in the following year.

1660 ............................................. The Royal Society of London, the first scientific society, is founded.

1665 ............................................. British scientist Robert Hooke publishes *Micrographia*, in which he describes the cells of plants.

1665–1666 ...................................... Isaac Newton develops calculus, deduces the laws of motion, derives a mathematical description of gravity, and conducts key experiments in optics.

1677 ............................................. Anton van Leeuwenhoek uses the microscope to discover single-celled organisms.

1687 ............................................. Newton's great work *Principia* is published.

1743 ............................................. Benjamin Franklin helps establish the American Philosophical Society—America's first scientific society.

1747–1752 ...................................... Franklin's electrical experiments lead to the invention of the lightning rod and the theory of electricity as a single fluid.

1785 ............................................. Scottish geologist James Hutton publishes *Theory of the Earth*, in which he proposes that geological changes

occur gradually over immense spans of time.

1796........................................ French mathematician Pierre Simon Laplace proposes the nebular hypothesis of the origin of the solar system.

1797........................................ Benjamin Thompson illustrates the mechanical equivalence of heat.

1799........................................ Alessandro Volta invents the electric battery.

1808–1827............................. English meteorologist John Dalton presents the atomic theory in *A New System of Chemical Philosophy*.

1820........................................ Danish physics professor Hans Christian Oersted discovers that electricity can produce magnetic fields.

1828........................................ German chemist Friedrich Wohler synthesizes urea.

1831–1836............................. British naturalist Charles Darwin serves as the naturalist aboard the *HMS Beagle.*

1859........................................ Darwin publishes *On the Origin of Species*.

1869........................................ Russian chemist Dmitri Mendeleev proposes his periodic table of the elements.

1873........................................ James Clerk Maxwell systematizes electromagnetic phenomena and predicts electromagnetic radiation.

1895........................................ German physicist Wilhelm Konrad Roentgen discovers X-rays.

1898........................................ Polish chemist Marie Curie, assisted by her husband Pierre, isolates the first of the radioactive elements.

1899–1904 ...................................... British physicist Ernest Rutherford makes fundamental discoveries regarding the nature of radioactivity.

1902 ................................................ American biologist Walter Sutton discovers egg and sperm have matching pairs of chromosomes.

1905 ................................................ Albert Einstein publishes three fundamental discoveries: the atomic origin of Brownian motion, the quantum nature of radiative energy, and the theory of special relativity.

1911 ................................................ Dutch physicist Heike Kamerlingh-Onnes discovers superconductivity in a sample of mercury at 4 degrees kelvin.

1924 ................................................ American astronomer Edwin Hubble discovers that galaxies are immense collections of billions of stars.

1932 ................................................ Particle physicist Carl Anderson discovers antimatter.

1945 ................................................ American scientists develop the atomic bomb.

1952 ................................................ American biochemist James Watson and British crystallographer Francis Crick solve the double helix structure of DNA.

1953 ................................................ Chemists Stanley Miller and Harold Urey synthesize amino acids in a chemical experiment designed to mimic the early Earth's atmosphere and ocean.

1959 ................................................ Cornell physicists Giuseppe Cocconi and Philip Morrison propose a search for extraterrestrial intelligence.

1964 ................................................ Molecular biologists crack the genetic code of DNA and RNA.

1965 ................................................ American oceanographer Drummond Matthews and British geophysicist Frederick Vine report on strips of magnetically-aligned rock on either side of mid-ocean ridges.

1969 ................................................ American astronauts land on the Moon and return samples from the lunar surface.

1972 ................................................ American paleontologists Stephen Jay Gould and Niles Eldridge propose the theory of evolution by punctuated equilibrium.

1977 ................................................ American oceanographer Jack Corliss discovers ecosystems at volcanic vents a mile or more deep on the ocean floor while diving in the submersible Alvin.

1980s .............................................. NASA's Voyager 1 and 2 spacecraft visit the outer planets of the solar system.

1985 ................................................ A region over the Antarctic with seasonally reduced ozone, now called the ozone hole, is discovered by British scientists.

1986 ................................................ The first of a new class of high-temperature superconductors with ionic bonds is discovered by IBM scientists.

1990 ................................................ NASA's Hubble Space Telescope is launched.

1996 ................................................ British biologist Ian Wilmut clones a sheep named Dolly from an adult cell.

# Glossary

**acid rain**: the formation of acidic rain drops by reaction with chemicals produced by burning fossil fuels.

**alleles**: different forms of a gene, some of which may be dominant and some, recessive.

**alternating current (AC)**: electricity produced by a generator, in which electrons move back and forth.

**amino acids**: molecular building blocks of proteins.

**animals**: multicellular organisms that obtain their energy and raw materials from the biomolecules of other organisms.

**antimatter**: particles that, when combined with their oppositely charged matter particles, annihilate to form energy.

**astronomy**: the science of collecting, analyzing, and interpreting photons from space.

**atom**: a submicroscopic particle from which solids, liquids, and gases are made.

**atomic number**: the number of protons in an atom, which defines the element.

**battery**: a device that applies a continuous motive force to electrons.

**big bang theory**: the theory that proposes that the universe came into existence at one moment in time, and subsequently has undergone rapid expansion.

**biology**: the study of living systems.

**black hole**: the collapse of the remnants of a massive star into a point, from which even light cannot escape.

**cancer**: a disease that occurs when defects in the genetic machinery cause a cell to divide again and again to form a tumor.

**carbohydrates**: energy-rich molecules composed of carbon, hydrogen, and oxygen; the most abundant biomolecules on Earth.

**cell**: the basic unit of all living things.

**Cenozoic Era**: the period of Earth history from 65 million years ago to the present; the age of mammals.

**chemical reactions**: the breakdown or rearrangement of atoms into different substances.

**chemistry**: the study of atomic interactions.

**chromosome**: the structure in a cell that carries genes in the chemical DNA.

**climate**: a long-term average of weather for a given region.

**computer**: a machine that stores and processes information.

**conduction**: the movement of heat by atom-to-atom contact.

**convection**: the movement of heat by transfer of a mass of fluid.

**convergent boundary**: a plate boundary where two plates move together.

**core**: the inner metallic layers of the Earth.

**covalent bond**: a chemical bond in which two or more atoms share electrons.

**crust**: the outer layer of the solid Earth.

**deoxyribonucleic acid (DNA)**: the chemical that carries genetic information.

**direct current (DC)**: electricity produced by a battery, in which electrons flow in one direction.

**divergent boundary**: a plate boundary where two plates move apart and new crust is formed.

**earth science**: the study of our planet's history and present dynamic state.

**earthquakes**: sudden Earth movements that result from the gradual buildup of stress and subsequent fracture between two blocks of rock.

**ecosystems**: complex communities of organisms and their physical environment.

**electric circuit**: a system that incorporates a source of electrical energy, a device that responds to this electrical potential, and a closed loop of conducting material.

**electricity**: the motion of electrons in a closed circuit.

**electromagnetic radiation**: a form of wave energy produced whenever an electric charge accelerates; travels at the speed of light.

**electromagnetic spectrum**: the continuum of all possible wavelengths of electromagnetic radiation, including radio, microwaves, infrared radiation, light, ultraviolet, X-rays, and gamma rays.

**electron**: subatomic particle that carries a negative electric charge and participates in chemical bonding.

**element**: a substance that cannot be broken down into other substances by any ordinary physical or chemical means.

**energy**: the ability to do work.

**entropy**: the ratio of heat energy over temperature; a measure of the disorder of a physical system.

**eukaryotes**: single-celled organisms with a nucleus and other organelles.

**evolution**: the process by which life has changed over billions of years of Earth history.

**extinction**: the disappearance of a species.

**fission reactions**: nuclear reactions that split an atom.

**force**: the phenomenon that causes an object to accelerate.

**fossil**: any evidence of ancient life; usually preserved in rock.

**fossil fuel**: a carbon-based fuel obtained from the Earth, including coal, petroleum, and natural gas.

**fungi**: organisms that resemble plants in terms of their cell structure and growth patterns, but are nonphotosynthetic.

**fusion reactions**: nuclear reactions that combine two nuclei, usually hydrogen.

**galaxies**: collections of billions of gravitationally bound stars.

**genetic disease**: a disease that arises from a defective gene.

**genetic engineering**: the process of consciously altering a coded sequence of DNA or RNA to produce an organism with new characteristics.

**genetics**: the study of the ways by which biological information is passed down from parents to offspring.

**gravity**: an attractive force that exists between any two masses.

**greenhouse effect**: the warming of the Earth's surface by atmospheric gases, notably carbon dioxide, that trap infrared radiation.

**Human Genome Project**: a project that will provide a detailed map of the distribution of genes on the 23 human chromosomes, and the sequence of bases.

**hydrocarbons**: compounds of carbon and hydrogen.

**igneous rocks**: all rocks that form from a molten state.

**ionic bond**: a chemical bond that forms through an exchange of one or more electrons.

**isotope**: an atom for which the number of protons and neutrons are known.

**istocacy**: an earlier geological concept that held that mountains were great rafts of relatively light material buoyed up like icebergs on the ocean.

**laser**: a device that emits an intense narrow light beam of a single wavelength (an acronym for Light Amplification by Simulated Emission of Radiation).

**leptons**: a class of six particles, including electrons and neutrinos, that do not occur in the atom's nucleus.

**Linnaean system**: the system of nomenclature that assigns a specific name to each kind of organism.

**lipids**: biomolecules including fats, oils, and waxes; building blocks of cell membranes.

**lithosphere**: the strong rock layer that includes the crust and the top part of the mantle of the Earth; it is relatively thin, cold, and brittle and is typically between 50–100 km in thickness.

**mantle**: rocky layers of the Earth interior; mantle convection drives plate tectonics.

**mass**: an object's tendency to resist an acceleration.

**mass extinction**: a time in geological history when a large percentage of species become extinct.

**Mesozoic Era**: the period of Earth history from 248 to 65 million years ago; the age of dinosaurs.

**messenger RNA**: the molecule that copies the base sequence of a DNA segment (a gene) letter by letter.

**metabolism**: the cell's process of obtaining and using energy from its surroundings.

**metallic bond**: a chemical bond that forms when all atoms release electrons, creating a "sea" of negatively charged electrons with positively charged atoms interspersed.

**metamorphic rocks**: all rocks whose mineralogy is altered by the effects of temperature and pressure.

**microchip**, or **integrated circuit**: a semiconductor device that may incorporate thousands of transistor-like regions.

**natural selection**: the theory that life evolves by the gradual, selective transmission of desirable traits from one generation to the next.

**nebular hypothesis**: a widely accepted model for the formation of stars, including the solar system.

**neutrons**: electrically neutral nuclear particles with mass slightly greater than that of a proton.

**nuclear reactor**: a device that produces electrical energy by sustained nuclear fission reaction.

**nucleus** (of atoms): tiny object that carries most of an atom's mass.

**nucleus** (of cell): the central organelle of eukaryote cells; contains the cell's DNA.

**organelles**: discrete internal structures in a eukaryotic cell; the nucleus is an example.

**organic chemistry**: the field of chemistry devoted to carbon compounds.

**ozone hole**: a region over the Antarctic with seasonally reduced ozone.

**ozone layer**: a region of the stratosphere, containing small amounts of the gas ozone ($O_3$), which absorbs much of the Sun's harmful UVB ultraviolet radiation.

**paleoclimatology**: the study of ancient climates.

**Paleozoic Era**: the period of Earth history from 543 to 248 million years ago, characterized by the appearance of animals with hard parts.

**phase transformation**: a change in state or atomic structure, often resulting from changes in temperature or pressure.

**photon**: an individual packet of electromagnetic radiation.

**physics**: the study of matter in motion.

**plants**: multicellular organisms that obtain their energy from the sunlight.

**plastic**: a solid formed from complexly intertwined polymer strands.

**plate tectonics**: the theory that the surface of the Earth is divided into about a dozen thin, brittle, mobile plates.

**polymer**: a large molecular structure composed of chains of small molecules.

**polymerase chain reaction (PCR)**: a technique to duplicate a specific strand of DNA.

**Precambrian**: the period of geological history before 543 million years ago.

**prokaryote**: single-celled organisms without any well defined internal structures, such as a nucleus.

**proteins**: chemical workhorses of life, built from chains of amino acids, their structure determines their function.

**proton**: positively-charged nuclear particle, present in all atoms.

**pulsar**: a neutron star that emits brief sharp pulses of energy as opposed to the steady release of energy typically encountered.

**punctuated equilibrium**: the theory of evolution that claims species change in relatively sudden bursts.

**quantum mechanics**: the study of motions at the scale of quantum jumps.

**quarks**: a class of six different particles that combine in twos or threes to form neutrons, protons, and other nuclear particles.

**radiation**: the movement of heat by electromagnetic radiation; also the energetic particles produced by radioactive atoms.

**radioactivity**: the spontaneous release of nuclear energy from an atom.

**relativity**: the theory that the laws of nature are the same in every reference frame.

**ribonucleic acid (RNA)**: the molecule that transforms DNA into proteins.

**scientific method**: a cyclic process of inquiry based on observations, synthesis, hypothesis, and predictions that lead to more observations.

**sedimentary rocks**: all rocks that are deposited in layers.

**seismology**: the study of the Earth with sound waves.

**semiconductors**: materials that conduct electricity, but not very well.

**SETI**: the search for extraterrestrial intelligence; involves looking for characteristic radio signals from nearby Sun-like stars

**solar system**: all objects that are gravitationally bound to the Sun.

**spectroscopy**: the study of light-matter interactions.

**states of matter**: solid, liquid, gas, and plasma, which are manifestations of submicroscopic organization of atoms.

**superconductors**: materials that conduct electricity without any resistance.

**supernova**: the sudden collapse and subsequent explosion of a star.

**taxonomy**: the formalized procedure for classifying and naming life forms.

**transfer RNA**: the molecule that matches three bases on messenger RNA to an amino acid.

**transform boundary**: a plate boundary where two plates move past each other.

**virus**: a strand of genetic material (DNA or RNA) surrounded by a coating of proteins; viruses can take over a cell's genetic machinery.

**volcano**: a mountain or other feature that forms when molten rock erupts as lava and accumulates at the surface.

**waves**: a way to move energy without moving mass.

**weather**: the state of the atmosphere at a given time and place.

**work**: the exertion of a force over a distance.

# Biographical Notes

**Aristotle** (384–322 B.C.). Athenian philosopher whose writings on mathematics, physics, and biology, and development of the inductive method, were influential for more than 1,800 years.

**Niels Bohr** (1885–1962). Danish physicist who proposed an atomic model in which electrons adopt specific energies and shift from one energy to another in quantum jumps.

**Tycho Brahe** (1546–1601). Danish astronomer who advanced the field principally by designing, constructing, and using instruments that greatly increased the precision and accuracy of astronomical observations.

**Henry Cavendish** (1731–1810). British physicist who determined experimentally the value of the gravitational constant, and thus the mass of the Earth.

**Nicolas Copernicus** (1473–1543). Polish astronomer who devoted much of his life to developing a mathematical model of the solar system in which the Earth and other planets orbit the Sun.

**Charles Coulomb** (1736–1806). French physicist who determined the force law between two charged objects: Force equals the product of the two charges divided by the square of the distance between them, times an appropriate constant.

**Francis Crick** (1916– ). British crystallographer who, in 1952, worked with James Watson to solve the DNA structure.

**Marie Sklodowska Curie** (1867–1934). Polish-born chemist who spent much of her career working with her husband Pierre in Paris. The Curies refined tons of high-grade uranium ores to extract small quantities of the previously unknown elements polonium and radium.

**John Dalton** (1766–1844). English meteorologist who presented the first statement of the modern atomic theory—that matter is composed of atoms of perhaps several dozen varieties that differ in their weights and sizes.

**Charles Darwin** (1809–1882). British naturalist who, after serving as naturalist on the voyage of the *HMS Beagle* from 1831–1836, developed the theory of biological evolution by natural selection.

**Humphry Davy** (1778–1829). British chemist who pioneered the use of the battery to isolate chemical elements.

**Democritus of Abdera** (c.460–370 B.C.). Greek philosopher who developed a philosophical rationalization for atoms, which are indestructible, but may be rearranged to form different substances.

**Albert Einstein** (1879–1955). German physicist who made several fundamental contributions to science. In 1905, alone, Einstein demonstrated the atomic origin of Brownian motion, provided compelling evidence for the quantum theory of matter, and produced the first installment of his theory of relativity.

**Michael Faraday** (1791–1867). British physicist who, in 1831, discovered electromagnetic induction and inventor of the electric generator.

**Benjamin Franklin** (1706–1790). Famous American statesman and signer of the Declaration of Independence, who devised an explanation of electrical phenomenon.

**Rosalind Franklin** (1920–1958). British crystallographer and chemist who obtained the first X-ray photographs of DNA in the early 1950s.

**Galileo Galilei** (1564–1642). Galileo transformed both the content and the methodology of science. He was a pioneer in the design of elegant experiments to study the physics of motion, and he was the first astronomer to use the telescope; his discoveries ultimately led to his heresy trial in 1633.

**Luigi Galvani** (1737–1798). Italian anatomist who noticed that the leg of a dead frog would twitch when two different metals were touched to each other and to the exposed nerves of the leg, even when no electric shock was applied.

**William Gilbert** (1544–1603). English physician and physicist who systematized his own magnetic investigations with earlier work to show that the Earth, itself, is a giant magnet with its own field.

**Werner Heisenberg** (1901–1976). German physicist who expressed the uncertainty principle, which states that you can't know the exact position and velocity of an object at the same time.

**Robert Hooke** (1635–1702). British physicist and microscopist who discovered units of plants, which he called "cells."

**Edwin Hubble** (1889–1953). American astronomer who, in 1924, discovered that galaxies are immense collections of gravitationally bound stars far outside our own Milky Way galaxy. He observed that many galaxies are receding at velocities proportional to their distance.

**James Hutton** (1726–1797). Scottish geologist who proposed the doctrine of uniformitarianism, that great geological changes take place through countless decades of gradual increments.

**James Prescott Joule** (1818–1889). British physicist who helped to develop the first law of thermodynamics and the mechanical theory of heat.

**Johannes Kepler** (1571–1630). Tycho Brahe's mathematically gifted assistant, who analyzed data for Mars and derived three laws of planetary motion.

**Pierre Simon Laplace** (1749–1827). French mathematician who developed the generally accepted model for star formation by gravitational attraction of dust and hydrogen gas into an ever denser, more compact cloud, which flattens into a rotating disk.

**Antoine Lavoisier** (1743–1794). Influential French chemist, who contributed to the understanding of oxidation and stated its importance in respiration. Lavoisier favored the caloric theory of heat.

**Anton van Leeuwenhoek** (1632–1723). Amateur Dutch scientist who was the first to make extensive use of the microscope in the 1670s, and who discovered the abundance of microscopic life.

**James Clerk Maxwell** (1831–1879). Scottish physicist who presented four equations that codified every aspect of electromagnetism, including the previously unrecognized phenomenon of electromagnetic radiation.

**Johann Gregor Mendel** (1822–1884). Czechoslovakian botanist and monk who was the founder of classical genetics. Mendel developed his laws of heredity during more than 28,000 separate cross-breeding experiments on pea plants.

**Dmitri Mendeleev** (1834–1907). Russian chemist who, in 1869, systematized the weights and chemical properties of 63 chemical elements in his periodic table of the elements.

**Isaac Newton** (1642–1726). British natural philosopher and mathematician who made fundamental discoveries in several branches of study. During the remarkable period of 1665–1666, Newton developed calculus, the laws of motion, the law of universal gravitation, and principles of optics and light. Many of his ideas were summarized in the Principia of 1687.

**Robert Norman** (c.1550–1600). British sailor and instrument maker who described the dip of compass needles. His work foreshadowed the concept of a magnetic field.

**Hans Christian Oersted** (1777–1851). Danish professor of physics who, while lecturing in front of a classroom in 1820, discovered that electricity can produce magnetic fields.

**Louis Pasteur** (1822–1895). French chemist who debunked the prevailing idea of spontaneous generation. Pasteur's dictum of "No life without prior life" pushed back origins to an inconceivably remote time and place.

**Max Planck** (1858–1947). German physicist who, in 1900, proposed the idea that energy comes in discrete bundles, called "quanta," at the atomic scale. This theory helped to explain the spectrum of electromagnetic radiation emitted by a "black body" that absorbs all electromagnetic radiation that falls upon it.

**Pliny the Elder** (23–79). Roman scholar who catalogued thousands of "facts" that were known to him or sources he deemed to be reliable, in his 37-volume *Natural History*.

**Ptolemy of Alexandria** (c.100–170). Greek astronomer who proposed an Earth-centered model that incorporated circular orbits modified by secondary circles, called epicycles.

**Ernest Rutherford** (1871–1937). New Zealand-born British physicist whose studies of radioactivity led to experiments that demonstrated the existence of the atomic nucleus.

**Benjamin Thompson** (1752–1814), known as Count Rumford. American-born inventor who demonstrated that heat is a form of mechanical work and thus is equivalent to energy.

**William Thompson** (1824–1907), known as Lord Kelvin. British physicist who made significant contributions to understanding the laws of thermodynamics.

**Alessandro Volta** (1745–1827). Italian physicist who invented the battery in 1794.

**James Watson** (1928– ). American biochemist who, in 1952, worked with Francis Crick to solve the DNA structure.

# Bibliography

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